SPACE AND ITS DIS-CONTENTS : NEW DIRECTIONS FOR INTRINSICALITY, SUBSTANCE AND DIMENSIONALITY

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Abstract

This dissertation examines key areas in ontology through the intersection of metaphysics and physics. I argue that modern physics gives us good cause to look for new metaphysical models in place of the classical conceptions of ‘object’ and ‘space’. Part I addresses the object in itself, wherein I argue that physics, along with various philosophical concerns, encourages us to re-evaluate the intrinsic/ extrinsic distinction in favour of new classifications. In particular, I use conclusions of relativity theory and the acquisition of mass via the Higgs field as indications of the inadequacy of intrinsicality, concluding that the distinction is more trouble than it is worth.

Part II examines the intersection of objects and space, wherein I criticise substantivalism and promote singular fundamental ontologies like relationalism and supersubstantivalism. I examine phenomena like spatial expansion and field theory as well as separability issues more generally to emphasise the lack of rationale for a substance dualism of ‘object material’ and ‘space material’. I also challenge the coherence of substantivalism’s ‘occupation relation’ and the ease of interpreting mathematical models into physical terms. I conclude that, again, the classical notion of ‘object’ and its substantival framework are misplaced and should be put aside in favour of developing monistic ontologies.

Part III looks at space in itself and the properties commonly attributed to it. I explore issues of separability using key experiments, and what makes spaces ‘physically real’, before an extended examination of dimensions and dimensionality, highlighting the confusion physicists express toward such a ubiquitous concept in modern physical theories. I also explore how we use dimensions and reasons for adopting realist or instrumentalist approaches toward them, arguing that much more work should be focused on this area. I conclude with ways in which physics motivates new metaphysical models and suggest improvements for future methodological partnerships.

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Introduction

This dissertation examines key areas in ontology through the intersection of metaphysics and physics. I argue that modern physics gives us good cause to look for new metaphysical models in place of the classical conceptions of 'object' and 'space'. In this, I principally argue that

> 1) there are far fewer intrinsic properties than classically conceived and the traditional intrinsic/extrinsic distinction is more trouble than it is worth, and should be jettisoned,
>
> 2) current substantivalism should be put aside to develop more comprehensive monistic ontologies, and
>
> 3) the formal study of 'dimensions' should be a key metaphysical topic.

In this, I take science, and physics in particular, as giving our best account of the world and as offering models that can be valuably analysed on their own terms, with certain cautions; as we are now well aware, there are lots of models that make sense of the data and no way to wholly remove ourselves from the data recovery process. These are insightful, and seemingly intractable, concerns, which will nonetheless be largely put aside here in an effort to let criticisms of particular hypotheses get off the ground. With that understanding in place, I will help myself to many of the more perplexing physical phenomena in an effort to reconfigure classical models for a better understanding of *this* universe.

There is a classical and (generally) pre-theoretical way of looking at the world that understands it at a human scale; there are objects, like chairs and rabbits and boats, that move or are moved about. We, as special *observers* as well as objects, create special relations between some of those objects—grouping them together where we find similar qualities or quantities (e.g. 'plums', 'my possessions', 'London' '5'), and articulating patterns for our use and amusement (e.g. f = ma). We are particularly fond of some properties—like position—and some patterning tools—like geometry and mathematics—that have made the postulation of first 'space' and now 'spacetime' both common and useful. Together, objects and spacetime create a fundamental ontology, which we have tried to use to accommodate the growing list of phenomena that include things like electrons, virtual particles, fields and gravity, with mixed success. To better address the discrepancies we might try to tweak the categories for the new phenomena to fit, or we might alter the categories altogether. Exploring options for the latter is a central theme to this research, guiding the rejection of the intrinsic/extrinsic distinction for more useful models, the consideration of singular substance ontologies, and the review of the main characteristics attributed to space.

The following chapters pursue this in greater detail, offering something of a selection of case studies where metaphysics and physics can inform each other, specifically in this (and not any possible) world. This is part of a larger concern that metaphysics should be working in concert with physics, helping to scout out options and implications not only for physics (as practitioners and philosophers of the subject generally do), but for ourselves and our way of thinking critically about the world. In light of this, I find each of the issues raised to demonstrate various ways that physics points away from completely self-contained and separable objects interacting in a background container. If philosophy discards its strict taxonomies of separate objects, we might embrace new frameworks of explanatory coherence, new descriptions of causation, or new (and perhaps fewer) constraints on identity.

The work is divided into three parts, each comprising several related chapters. Part I addresses the object in itself, wherein I argue that physics, along with various philosophical concerns, encourages us to re-evaluate the intrinsic/ extrinsic distinction and even to reject it in favour of new classifications. I begin with a review of classical objects and a quick survey of some of the roles of intrinsic properties that come with that view. The role of intrinsicality in picking out the fundamental, global, properties of our world is particularly compelling, and I use it as a guide when looking to find the best definition we should give to intrinsic properties.

I also adopt David Lewis' account of the term as those properties independent of any other thing, and try to make sense of the ancillary concepts of 'dependence', 'duplication' and an object in a 'contracted' universe in chapter 2, and in particular, I take causal dependence to be the most useful and accessible understanding of 'dependence'. Chapter 3 focuses on physical phenomena like the acquisition of mass via the Higgs field and the blurring *in principle* of object boundaries and thus their dependence relations, as indications of the inadequacy of intrinsicality. In chapter 4 I review options for reconceptualising the distinction, but conclude that 1) far fewer properties (possibly none) are intrinsic than classically conceived, and 2) the intrinsic/ extrinsic distinction is more trouble than it is worth in metaphysics and should be jettisoned.

Part II examines the intersection of objects and space, wherein I criticise substantivalism and promote singular fundamental ontologies like relationalism and supersubstantivalism. In chapter 5 I briefly survey each of these theories, noting their strengths and weaknesses, before ending with an in-depth review of supersubstantivalism as the newest member of the debate and as one of the ontological theories I find preferable to the substantival model. In chapter 6 I examine phenomena like field theory, spatial expansion, spatial vacuum and the possibility of spatial emergence to emphasise the lack of rationale for a substance dualism of 'object material' and 'space material'. I argue that these phenomena are suggestive of a monistic, rather than dualistic fundamental ontology with spatial expansion in particular raising questions for substantivalism. In chapter 7 I challenge the coherence of substantivalism's 'occupation relation'; while noting the useful options for object models that *happened* to come from substantival theorising, I note that these possibilities are not reliant on that framework and can be pursued under monistic substance approaches. I also explore the challenge of interpreting substantival mathematical models into physical terms, whereby we often follow formulae blindly to such an extent that we lose connection with physical reality. I conclude that, again, the classical notion of 'object' and its substantival framework are misplaced and that the latter should be put aside in favour of developing monistic ontologies.

Part III looks at space in itself and the properties commonly attributed to it. In chapter 8 I examine the expectation that space separates objects, reviewing several key experiments that indicate the nonseparability of space (spatial separation does not guarantee causal separation) before looking at nonseparability more generally. In chapter 9 I explore the distinction between 'physically real' and 'abstract' spaces, highlighting the uncertainty surrounding distinguishing characteristics and suggesting several. The remaining three chapters focus on dimensions, with chapter 10 outlining the confusion even physicists express toward such a ubiquitous concept in their theories.

Chapter 11 explores how we use dimensions, including as a means of theory unification, geometrisation and a tool for ordering information. Chapter 12 looks at reasons for adopting a realist or instrumentalist approach toward them, arguing that much more work should be focused on this area. I conclude with ways in which physics motivates new metaphysical models and suggest improvements for future methodological partnerships. Thus, when concerned with describing *this* universe—as this project is—the demise of 'the classical object framework' leaves us with reasons to develop more useful distinctions than intrinsic/ extrinsic properties, less bloated and mysterious ontologies than that of substantivalism, and to actively investigate dimensionality.

PART I: Objects in Themselves: the Demise of the Classical

Perfect Euclidean solids were once thought to give the underlying form to types of matter, and it has only been a lineage of small variants on that theme until the last century, when dramatically different and untidy models were favoured. The untidiness comes in the loss of sharp boundaries and in the development of interconnected systems, values and operations that affect both our conception of an object and the way we do science. This scientific shift has been slow to infiltrate philosophical discourse for both good reasons (we have learned to be cautious of scientific claims) and bad (we'd rather not bother), and it is the collision of this changing physical landscape with classical conceptions of objects that I want to examine first. That is, I want to see what, exactly, we can say about objects themselves, particularly as concerns the idea of intrinsic properties.

This is important in itself, but also directly relates to larger theories of ontology; some relationalist theories begin and end with objects while other extreme substantival theories dispense with them altogether. To really make sense of these metaphysical approaches, we should have some account of what sort of thing an object is in itself. By looking at modern physics, we can assess whether 'object' and 'environment' are robust terms in modern physics and, specifically, we will investigate the long-revered notion of intrinsicality that is both somewhat mysterious and misshapen, a quasimodo concept that promises great fruits which, I argue, it is incapable of delivering in our world.

First, I examine several of the philosophical purposes intrinsicality serves, and briefly review how the literature defines intrinsicality; my goal here is not to trawl through the Lewis-Langton/Kim archives on the subject—which I think have received adequate attention—but to go straight to their best formulations and see what they can do. Second, I explore some of the philosophical problems these definitions face. Third, I argue that modern physics in particular fails to corroborate (and often contradicts) our traditional conception of intrinsic properties—not least because our traditional conception of an object fails to accommodate modern physics. Fourth, I explore some of the implications of these challenges, and, finally, I review whether there is any reason to salvage the intrinsic/ extrinsic distinction and the ways in which we might do it, concluding 1) far fewer properties (possibly none) are intrinsic than classically conceived, and 2) the intrinsic/ extrinsic distinction is more trouble than it is worth in metaphysics and should be jettisoned. Although I review alternative conclusions in chapter 4, including the continued use of traditional intrinsicality for practical purposes just as Newtonian mechanics is still often used in place of Einsteinian mechanics, a radical reconstitution of the general notion of intrinsicality is needed.

CHAPTER 1: Classical Objects and Intrinsicality

One of the principal ways we distinguish an object from its environment is by delineating the characteristics it has considered in and of itself, that is, its intrinsic properties. The notion of intrinsicality has traditionally appeared prominently in metaphysical debates, including debates about persistence over time, defining duplicates, object identity, supervenience claims and ontology. Although an exact definition of 'intrinsic' has proven elusive, the intuitive distinction between intrinsic and extrinsic properties seems commonsensical. After all, it seems so easy to conceptualise *extrinsic* properties, to talk about the external relations that something has, that *intrinsic* properties must be the remaining properties of the thing as it is in itself.

Despite facing growing challenges from physics as well as philosophical issues, the intrinsic/extrinsic distinction—amongst properties in particular—is still liberally used[1]. Intrinsicality is so tempting because it offers the idea of how something *really* is, separate from any surrounding confusions of circumstance, precedence etc.; to be intrinsic to an entity is to be *in virtue of the entity* itself; to have certain properties intrinsically is to have them without reference to external objects. On closer inspection, however, we find that the ease of separating the 'object in itself' from its surroundings is only superficial, and our traditional intuitions about 'dependence' are flawed. In this chapter, I first survey and disambiguate common roles for intrinsicality, before critically reviewing popular definitions of the concept.

1.1 Roles of Intrinsicality

Some of the most important philosophical roles of intrinsicality are the following, which I will examine in turn: to 1) differentiate between mere circumstantial change and real change, 2) help understand 'duplication', and 3) help determine which properties are the most fundamental. As the world's physical evidence grows more difficult for our intuitions of intrinsicality to accommodate, however, we find our expectations of intrinsicality doing us a disservice. In advancing our understanding of the intrinsic/extrinsic distinction I will review the connected and often explanatory notions of 'real change', 'duplication', 'naturalness' and

[1] See Brian Weatherson's 'Intrinsic and Extrinsic Properties' 2008 for an overview.

‘fundamental’ to see if we can better understand its uses before attempting a precise definition.

1.1.1 Change

Intrinsic properties have been used to define when something within a world *really* changes as opposed to a mere change in predicates, or ‘Cambridge change’ (e.g. acquiring the property *has a sister*). Thus, many argue that “a change in intrinsic properties is a real change in an object, whereas change in extrinsic properties isn’t” (Vallentyne, 1997, p.209). As innocuous as this might seem, two rival theories of object persistence—endurantism and perdurantism—have arisen from different interpretations of this belief. David Lewis controversially criticised the idea that objects can wholly exist at different times (endurantism) by claiming, among other things, that the same object could not then undergo *real* change: intrinsic properties would be “reinterpreted as relations that something with an absolutely unchanging intrinsic nature bears to different times. The solution to the problem of temporary intrinsics is that there aren’t any temporary intrinsics” (Lewis, 1986, p.204).

That is, if a fire poker has the properties *hot at* t_1 and *cold at* t_2 then it looks like the poker never changed and statically holds those time-indexed properties for all eternity. To avoid this traditional concern between ‘Cambridge change’ and *real* change, Lewis promotes the idea that objects only partially exist at each moment, persisting as the same object by having different temporal parts (perdurantism). While others are certainly keen to avoid making an object’s location in time and space an intrinsic property, they do not all conclude that we must therefore subscribe to perdurantism (Vallentyne, 1997, p.215-17). Indeed, one may be happy to *define* object change by the loss or gain of an intrinsic property without relying on a perdurantist view of persistence.

What one expects of intrinsic properties and their possible relations can thus affect one’s model of persistence, but I think we should be cautious of our assumptions for this role. First, it is certainly not obvious that intrinsic properties cannot change, and while it may well be that *F*-ness is a *relation* to a time, that property relation need not be seen as *caused* or *dependent* upon anything external, in the way that my mass can be a relation to my density but is not dependent upon it[2]. That is, I do not think that allowing F-ness to be a relation to a

[2]Since we measure time itself in terms of the perceived changes to an object (whether using the sun or a clock or a caesium atom), and relativity theory tells us that there is no privileged time frame, it seems we are making an

time means that F-ness is not intrinsic if we allow that it did not *depend* on that time. It is also unclear whether time is an external entity to be in a relation with, or if it is something more substantial; for instance, it might be more accurate to speak—as many physicists do—of the object's own worldline[3], and thus its own 'spacetime path' (much like an object's own spin or charge). If *its* time is intrinsic to it, then we have only established that one intrinsic property is related to another intrinsic property of the same spacetime object rather than depending on an extrinsic entity.

Second, there is a concern about the time required to 'capture' an intrinsic property. That is, when we say that something has intrinsic property P at time *t*, is 'time *t'* an arbitrarily small *philosophical* instant rather than the smallest known physical instant? How long is *t* and should it matter? These concerns are generally not addressed because most discussions of intrinsicality ignore the history that led to a thing being the way it is, so presumably by 'intrinsic' we mean that the properties of object X *at time t* are self-contained. But this 'time *t*' and the rationale for establishing its particular parameters are not well-defined.[4] Part of the importance of establishing a rationale for the parameters of *t* seems to lie with concerns over object change, and thus we ought to be aware of this often unmentioned temporal component in our formulations of intrinsicality in addition to any further metaphysical obligations (e.g. perdurantism). Intrinsicality, then, plays an important if controversial role in discussions of change, as well as in the attendant theories of persistence and identity.

1.1.2 Duplication

Intrinsic properties are often invoked to help enlighten the concept of 'duplication' or as a means of understanding shared histories among possible worlds. By duplication we understand that a duplicate of X will share all of the intrinsic properties of X, despite any variations of extrinsic properties and natural law. Intrinsic properties thus let us compare objects and possible worlds for similarities, ideally using such thought experiments to test other philosophical hypotheses or analyse internalist theses in epistemology. Duplication is closely connected with perfectly natural properties for Lewis, since the latter, along with perfectly natural relations, comprise the *intrinsic* nature of some particular, which in turn

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object be both *F* (at one time) and not *F* (at another time) in relation to 'another object being *G* and not *G*'. This does indeed sound extrinsic but I do not believe it is the sort of dependence we mean.

[3] The path of an object through a four-dimensional spacetime.

[4] This 'instant' can also get pushed down to the smallest known scale of the Planck length, at which point the notion of time becomes unclear.

determines whether something is a duplicate of that particular. Both duplicates and natural properties are significant to Lewis' work, but the web of definitions they create around intrinsic properties can direct us toward the next, and most scientific, role of intrinsic properties.

1.1.3 Fundamental Properties

Intrinsicality may be viewed as a marker of the most basic and inalienable entities of physics and of the universe's fundamental properties. Properties like *spin*, *mass* and *charge* seem plausible candidates for 'intrinsic' under this view, and it is this role of intrinsicality on which I wish to focus. Philosophically, we might try to get a handle on these by following Lewis and linking intrinsic properties with perfectly natural properties (Lewis, 1986, p.61), though the latter are a subset of the former and are never rigorously defined. In fact, aside from the intuition that some properties are more natural than others, this association with 'perfectly natural properties' does not seem to offer much insight.

There is some notion that 'perfectly natural' eschews disjunctive properties, but few people thought there were many disjunctive contenders anyway, and beyond this, 'naturalness' seems as vague a guide as intrinsic. For instance, it is unclear whether 'natural' encompasses everything (since it arises from nature) or whether it should include some level of arbitrarily designated fundamentality. Lewis merely notes that while one would prefer to do without contentious judgments of comparative naturalness, they have to be made and will conclude that things like 'mass' are more natural properties than 'my left foot'. While I agree with this gradation, the description of 'things like mass' is certainly not robust enough for our needs nor, ultimately, is the vague idea of 'perfectly natural properties'. Thus, I will set 'perfectly natural properties' aside and focus on the fundamental aspect.

The hope is that this would hit on the fundamental relations and properties of physics, allowing one's property *having mass* to be intrinsic but not one's property *hearing Beethoven's fifth*, or the property *wearing red shoes*. We might then assume that a world can be reduced to the intrinsic properties of things and the fundamental relations between them, with all else supervening on that[5]. This is an appealing suggestion in that it narrows the range

[5]However, there may be difficulty in distinguishing which entities possess some perfectly natural properties and in separating the properties from the relations (creating the same problem of separating the intrinsic and extrinsic). For instance, what appears to us to be relations between objects may be a single higher-dimensional property.

of what properties count as intrinsic to the most basic physical components, thus reducing the intrinsic/extrinsic distinction to a question of fundamental reduction. This approach is reflected in the physics literature as well, albeit with less rigorous standards of use, in that properties like *spin*, *charge*, or *momentum* are described as intrinsic and looked for in some form through all relevant interactions. This approach is akin to Yuri Balashov's suggestion that some object or interaction might have a zero-value for such a property, say, *zero momentum*, rather than claiming that the object or interaction lacked the property *momentum* (See Balashov 1999). It is roughly this application of 'intrinsic' as a tool to reveal such fundamental properties on which I will be focusing.

Following (Humberstone 1996), it may also be prudent to distinguish this sort of application of 'global intrinsic' as a *type* of (in some sense fundamental) property—as an intrinsic property *tout court* (Humberstone, p.206)—from a particular property's local relation to an individual. A global intrinsic property, then, is what we are looking for when we look to 'the' fundamental properties of our universe (*spin*, *charge* etc.). A local intrinsic property is what is intrinsic (generally by definition) to a given thing. That is, "whether a property is intrinsic [global], and whether some individual that has that property has it intrinsically [local], are different issues" (Weatherson 2008). That is, local intrinsicality need not translate into global intrinsicality since all squares will have the property *being a square or being next to a square* even though not *all* objects that possess the property will possess it intrinsically; i.e. those that possess it *in virtue of* being contingently next to a square, rather than by simply being a square (Humberstone, p.228). There is, however, an intimate connection between local and global intrinsic properties, particularly as we want some properties like *having charge* to be caught under both terms. Sticking to cases outside geometry and abstract definitions, I will use both senses of intrinsicality, though with emphasis on the global sense, to see if the term really can deliver the distinctions in practice that we want it to in principle.

1.2 Definitions

There are several ways one might define 'intrinsic' and none of them come without limitations. Although we frequently consult our intuitions, this approach proves suspect, particularly when addressing the unfamiliar worlds of modern physics where our intuitions are of little help. Not only does physics challenge intuitions of identity but the fundamental interconnections it poses challenge traditional notions of completely self-contained objects. It is not simply when Theseus' ship gets a board replaced that its constitution changes—it is at every instant down to unmeasurable (even in principle) levels through minute interactions. Such limitations of intuition will be important to remember as we look at possible definitions, especially as physics offers us a universe of fields and wave-particle duality, a fluctuating interplay of energy and mass surrounded by virtual ephemera.

I will here explore what I see as three increasingly explanatory definitions of intrinsicality that one might offer, as much to get some sense of what intrinsic properties are *not* as to see what they are like. I conclude with the definition most commonly invoked in the literature before discussing the many problems it (or indeed any of the definitions) faces. The related concept of 'dependence' will be addressed later, but it seems worth keeping in mind that I adopt a reading of this as *causal* dependence (see Chapter 2).

1.2.1 Essential

Firstly, one may take 'intrinsic' to be synonymous with 'essential', such that I have a property intrinsically iff I have it essentially—and without it I would not exist. The Aristotelian notion of essential properties is closely tied to identity and diametrically opposed to accidental properties, such that an object's essential properties are those "which it could never have lacked and which it could not lose without ceasing to exist or to be what it is" (Bigelow, Ellis and Lierse, p.374). I may have the accidental property of *being happy* or *having a made bed*, but none of that, the argument goes, changes what is essentially me, and neither does your having a cup of tea. All of these states of affairs appear extrinsic to me, whereas my issuing from the exact zygote I came from and having the capacity to remember things seems essential to what makes me, me[6].

Accepting this construction of intrinsicality poses further concerns however, as on the one hand it may arguably be both too weak *and* too strong, and on the other hand, it is no more illuminating than 'intrinsicality'. 'Essential' may be too weak a synonym for intrinsic in that we could imagine some of my essential characteristics not existing without relational or *extrinsic* environmental influences (e.g. my cognitive functions may be essential to me, but they are not physically possible without a sufficient intake of oxygen from the environment). Perhaps the extrinsic property *having a library nearby* or, if one believes numbers to exist, *being accompanied by the number 7* is essential to me. But this acceptance of spatiotemporally disparate things and environmental influences does not appear specific

[6] I am not attempting to range over abstract objects such as sets that may possess their members essentially.

enough for what physicists, or indeed many of us mean by intrinsic. Additionally, the definition may be too strong and depend too rigidly on internal or situational factors that overly restrict our notion of the intrinsic. Whether or not we take overtly external things as essential, we may mean that *everything* about an object is essential to it, for being *exactly* as it is. For example, depending on one's conception of identity fragility, it may be that the molecules of a contained gas are in their particular arrangement *essentially*, and it would not be the same gas if the molecules were differently organised. But this again is not what we tend to mean when we ask about something's intrinsic properties.

Essential, then, may carry further implications than we wish intrinsic to carry. But even if we were to embrace something akin to the weaker definition of essential, there is no clear set of properties that constitute what it means to be something *essentially*. That is, deciding what counts as an essential property seems as open to biased intuitions as deciding what counts as an intrinsic property. It may be that intrinsic properties are a subset of what is essential to something, but it appears that there is a useful distinction between intrinsic and essential that is lost in collapsing the two together. Regardless, the association between the terms does not get us any closer to a refined definition of intrinsic.

1.2.2 Non-Relational

Another tempting synonym for 'intrinsic' is the non-relational properties of an object. However, as (Humberstone 1996) highlighted, the two types of property are not synonymous, making 'non-relational' only a subset of 'intrinsic'. It is suggested that my relation to external bodies, systems etc. should not be seen as a property that I possess in any sort of intrinsic way—it is not something I possess across all or many possible worlds. My orientation in my environment and my relations to the things in it (e.g. the property of *being 3 metres from a sheep*) changes wherever I go, whereas my circulatory system or my mass are bound to me in a much more important and lasting way, and are candidates for intrinsic properties where my distance from the sheep is not. This focus on external properties as being relations to other objects (or ideas etc.) might lead one to think the distinction rests on a question of relation, but it is not a reduction to simply relational and non-relational properties.

(Humberstone 1996) helpfully separates intrinsic properties from non-relational, noting that many proposed intrinsic properties can arise from internal relations of structure or function; for example, it is an intrinsic property of 'normal' water that it has the relation of ‘twice as many hydrogen atoms as oxygen atoms’ (or 2 hydrogen molecules and 1 oxygen). Additionally, we might say that it is intrinsic to a square that it have four lines *related* in a certain way—that is, possessing four line segments related by meeting end to end on a 2-Dimensional plane. Intrinsicality, at least in this local sense, is more than merely encompassing the non-relational properties. Of course, one may object to this interpretation and discount all relational properties as intrinsic, and such reductionist approaches have used it to give a far more fine grained account of properties that appears closer to the fundamentals of physics (as we saw in 1.1.3). Again, however, I agree with Humberstone that ‘non-relational’ is not an ideal synonym, particularly if we are to allow any internal structure to objects possessing intrinsic properties. It also difficult when invoking non-relational to distinguish ‘relational properties’ from properties that we pick out relationally; it may be a matter of current ignorance or language that we best pick out some property by relating it to others. Guarding against this makes determining what counts as an intrinsic more difficult.

1.2.3 Spatially Internal

Thirdly, we may understand intrinsic properties to be those properties whose physical extent of manifestation are spatially internal to a decided object boundary and located at a particular region (e.g. the intrinsic properties of an egg are all those properties whose physical extent of manifestation are internal and inclusive of the shell such as *having a yolk*). This does seem to be a more promising route, but boundaries are a tricky subject given the complex *interconnections* between bodies revealed by modern science. Do we want absolutely anything within a boundary—assuming there is a clear one—to be intrinsic? This approach has two key issues: 1) it inherits all the problems of establishing clear object boundaries associated with physics, and 2) even if boundaries were clear, not all internal properties are intrinsic. Some internal things (like neutrinos or parts of the sandwich I ate at lunch) do not seem to be a proper part of us or dependent upon us in any way—they merely pass through. Thus, this definition does not seem to distinguish between the spatially internal properties that are unimportant happenstance and important properties arising in virtue of the object itself.

Of course, one may be willing to take on the neutrinos and accidental properties by simply embracing this internal definition. After all, under this conception we need not be so concerned with teasing out the surrounding forces from the structure of the object or with accurately gauging the proportionate strengths of the interactions; we can simply say that the gravitational field that is within such-and-such a boundary is intrinsic (internal) to the object, regardless of what it depends on or how it arose. What is intrinsic (internal) to the object at any given time may change and even depend upon disparate surroundings, but our concern is only with the properties the object displays in its set limits. The sporadic and non-interactive property *containing neutrinos* or the property *processing matter* is an intrinsic property so long as they are within us; for a time, they are intrinsically part of us. Under this definition of 'intrinsic', one makes fewer claims on the origin and operation of fundamental forces and focuses instead on the activities within a certain region of spacetime, which might be seen as a benefit.

However, even if we were to accept this definition of what it means to be intrinsic, we are left with unclear boundaries to objects that we may never be able to discern, which restricts our understanding of the properties solely dependent upon 'it'. The epistemological concern is forceful but the more pressing concern is the supposed fundamental indeterminacy of the quantum world. In this definition, then, much more work needs to be done to determine the ways in which properties change, how we secure the identity of the changing region of spacetime and how that enriches our understanding of the object and perhaps that species of object (these latter concerns are more fully explored in chapter 4). So for the cost of collapsing 'intrinsic' to 'internal' and taking on the evident accidental properties, our intuitive conception of intrinsic as something that captures how the entity *really* is in virtue of itself alone, has grown more demanding without receiving empirical benefits. Arguably, a more refined definition is needed, one that is strict enough to meet the intuitions of Lewis and Jaegwon Kim, among others, who envision intrinsicality as something independent of all externalities—a definition to which I now turn.

1.2.4 Independent of Externalities

Finally, then, one might embrace the more stringent definition of 'intrinsic' and classify such properties as not dependent upon what is going on beyond the object's boundary. That is, an intrinsic property is one held by an object independently of *any* other thing distinct from it. This seems to best address our *intuitive* conception of intrinsicality—gaining the widest use in the literature (Ellis 2001, Lewis 1983, Weatherson 2008)—and will be taken as the accepted conception of intrinsicality throughout. However, such a construction not only raises the concern of the previous definition (that of clear boundaries for an object), it also requires separating the object's independent, 'intrinsic' properties from any property that depends, even in part, on something else. Lewis provided several permutations of intrinsic all following this basic pattern. In this, he notes another role for intrinsicality in defining duplicates, which turns out to be a reciprocal relationship (addressed in the next chapter):

> The intrinsic properties of something depend only on that thing; whereas the extrinsic properties of something may depend, wholly or partly, on something else. If something has an intrinsic property, then so does any perfect duplicate of that thing; whereas duplicates situated in different surroundings will differ in their extrinsic properties (Lewis, 1983, p.197).

This definition has proved very popular in the literature, and I will take it as the best encapsulation of common intuitions concerning the possession of intrinsic properties[7]. Lewis went on to enhance his definition in later work, responding to Kim's earlier suggestion that an intrinsic property was a property that could be possessed by an entity that did not coexist with any *contingent* and distinct object[8]. This definition raises questions about what sorts of things are contingent, what counts as a distinct object and why this particular configuration reveals intrinsic properties. To get at complete independence, Lewis' own interpretation of this position portrayed the object as unaccompanied, or *lonely*, such that a property is intrinsic iff possessing or failing to possess the property is independent of loneliness or accompaniment (Langton and Lewis, p.334).

The thought was that, a property like *being an unaccompanied cube* could not be possessed when the object was both alone and when it was accompanied, so it would come out extrinsic. The property *being a cube*, however, was thought to persist in both environments. Interested in subsidiary taxonomies, Lewis (along with Rae Langton) argued for intrinsic properties using 'combinatorial analysis' (combining other modal desiderata with the search for intrinsic properties) that followed the modal profile of intuitively intrinsic properties, which:

> a) excluded troubling disjunctive properties (where each disjunct is much more natural than the whole disjunction),
>
> b) divided into basic and non-basic (where the latter supervene on the former),

[7] Because of the confusion surrounding intrinsicality, I am unable to distinguish the *possession* of an intrinsic property from the *instantiation* of one; that is, there is presently no way of knowing whether an object possesses an intrinsic property when not instantiating it so I will stay mute on this distinction.
[8] See Kim's 'Psychophysical Supervenience' 1982.

c) were *perfectly natural* properties, and

d) which could be illuminated by discussions of duplicates[9].

Although these classifications limit our options they do not determine a list of unbiased (not subject to competing intuitions with recourse for arbitration) intrinsic properties, despite Lewis' later claim that "we can confidently classify properties as intrinsic or not" (Lewis, 2001, p.390). Moreover, they are in danger of providing a tight definitional circle that "is too tight to be enlightening" (Langton and Lewis, p.345). It is not my business to get into the particulars of their arguments here, primarily because such classifications are most useful only when one already has a list of intrinsic properties at hand (Lewis, 2001, p.398). Rather, I wish to highlight their focus on intrinsic properties as either properties possessed in isolation, or properties that are independent of their accompaniment. This approach assumes that there is some objective 'other' world from which they may be viewed and in which they are 'truly' themselves.

Peter Vallentyne has followed a similar approach by seeking to capture the range of intrinsicality by degrees, namely the broad and narrow. In the broad sense, an intrinsic property is "appropriately independent of the existence of other objects…In the *narrow sense*, a property is intrinsic just in case it is intrinsic in the broad sense *and is a qualitative property*" (Vallentyne, p.215). Vallentyne uses the specification of qualitative properties to allow duplicates to share intrinsic properties even though they are not at the same location in spacetime, (thus, qualitative independent properties might include *redness* and *roundness*). Stephan Leuenberger moves away from degrees to argue that there are two distinct concepts of intrinsicality—constructed in terms of duplication and combinatorial principles—arguing against unifying them. Both concepts make use of the definitions of intrinsicality discussed in this section (namely, that intrinsic properties are those belonging to a lonely object in a certain way, and that intrinsic properties are those shared by duplicates), and rest on the independence of externalities. In its combinatorial form, then, "intrinsic properties are those whose instantiation by a thing does not imply anything for things distinct from that very thing" (Leuenberger, p.5).

[9] In Lewis, 2001, he also admits of mixed properties that are neither purely intrinsic nor extrinsic (e.g. the property *being a cube accompanied by another cube*). While this is an interesting compromise that may involve far more properties than the disjunctive examples considered, it is not adequately addressed and will be left aside for the sake of simplicity.

A similar account ('contraction') was given by Vallentyne in (Vallentyne 1997) that suggested intrinsic properties are those properties left to an object when all other objects are removed; that is, intrinsic properties are those left after a universal contraction to focus only on the object. He suggests that one may define intrinsic properties as those that an object would have if all other objects had been removed from the world. Although he grants that some objects may not be removable without simultaneously removing other objects or laws in general, and indeed, that there might not be a unique way of so *contracting* the world, he nonetheless posits that the end result of this contraction should demonstrate a thing's intrinsic properties (Vallentyne, p.213-4)[10]. Although operating in a slightly different metaphysical framework from Lewis, Vallentyne's suggestion is somewhat similar to Lewis and Langton's argument for intrinsic properties being those that an object has when lonely.

The basic idea in all these accounts is still that intrinsic properties are possessed independently of the object's environment, which seems central to our naïve intuition and expectation of what intrinsicality is, and is just the opposite of what it means to be extrinsic. As phrased by Stephen Yablo, an intrinsic property is what a "thing has (or lacks) regardless of what may be going on outside itself" (Yablo, p.479). Where 'essential' and 'internal' were inadequate, particularly for our focus on *global* intrinsicality, this latter definition seems to do the job. Indeed, it is this type of definition that has come to dominate the literature, offering an intrinsic/extrinsic distinction that is intuitively quite appealing, but upon closer inspection, the formulation of intrinsic as independent of externalities does not appear so satisfactory, as we will see in the next chapter.

[10] While noting the caveat that his notion does not distinguish between qualitative and non-qualitative properties, Vallentyne does offer the definition that property "P is intrinsic =df for any world w, any time t, and any object x: (a) if Px at t in w, then Ox at t in each x-t contraction of w, and (b) likewise for ~P" (Vallentyne, p.212).

CHAPTER 2: Philosophical Concerns

Despite its popularity, the definition of 'intrinsic properties' given by Lewis (those properties of an object that do not depend on any other thing, pick out duplicates, and would exist in a contracted universe) pose several enigmas, including what the nature of the referenced dependence is, and how one is to get a purchase on the concept of 'duplication'. Using this definition of 'intrinsic properties' given in 1.2.4, I now critically explore the ancillary concepts of 1) dependence, 2) duplication and 3) 'contracted' universes for the *true* properties of an object. In this, I challenge the utility of distinguishing between metaphysical, constitutive and causal dependence that Lewis and others seem to make, and I argue that neither duplication nor contraction is useful in determining intrinsic properties.

2.1 Dependence

Lewis argues that intrinsic properties do not *depend* on anything other than the thing itself, but in what does this dependence relation consist and does it clarify intrinsicality? In general, dependence involves a complex family of relations that encompass the ways one being may depend upon one or more other beings[11]. Dependence can be causal or ontological or metaphysical etc. and can be modally construed (Linnebo, p.77)[12], or simply understood as 'x depends on y if, necessarily, x exists only if y exists'. In teasing out the nuances of this relation, I will examine several interpretations of 'dependence' to see what use it might serve for Lewis' description of 'intrinsic' and whether a clearer notion of 'dependence' can lead us to an intuition-neutral account of intrinsicality. I conclude that metaphysical dependence fails to give instructive guidance when it comes to determining intrinsic properties. Additionally, the causal and constitutive interpretations of 'dependence' are neither helpfully different from each other nor able to accommodate many (if any) of the textbook examples of intrinsic properties.

2.1.1 Metaphysical

Bradford Skow suggests in (Skow 2007) that the type of dependence Lewis means is metaphysical, and understood in a modal way. That is, the Lewisian definition of 'intrinsic'

[11] See (Lowe 2009) for an overview.

[12] There are approaches that separate this classification into strong and weak dependence (as made by Øystein Linnebo) such that "*x strongly depends* on *y* if and only if any individuation of *x* must proceed via *y*. …[whereas] x *weakly depends* on *y* if and only if any individuation of *x* must make use of entities which also suffice to individuate *y*" (Linnebo, p.78).

seems to focus on whether an object's properties *metaphysically* depend on other objects, since some of his examples (e.g. 'shape') clearly *causally*—physically—depend on extrinsic factors. But it is difficult to get a clear grasp of what is special about metaphysical dependence and whether we should pin our understanding of the term to it. Like Lewis, Skow argues for this weaker conception to allow intrinsic properties a wide range of dependencies. For instance, the shape of sand in my hand *physically* "depends on the existence of my hands…But it is fine for an intrinsic property to physically depend in this way on the existence of other things. Intrinsic properties merely need to be metaphysically independent" (Skow, 2007, p.114). Skow allows for such renegotiations of dependence by appealing to possible worlds and thus steers the discussion of intrinsicality beyond the physical relations of our actual universe.

I cannot make much sense of this. If a property depends *actually* on other things, and perhaps may always actually depend on other things in our universe, what do we accomplish by imagining a scenario where things were different? Moreover, how are we to all agree on which properties can be appropriately imagined to be different? If by 'metaphysical dependence' we mean 'not prima facie definitionally independent', then we can get away with quite a lot and have no further tool to separate the *intrinsic* properties from other metaphysically possible properties.

That is, suppose a chair has the property *having a mass of 10kg*, and I claim that such a property of mass does not *metaphysically* depend on anything else. If you disagree, it does not seem that we can progress beyond this because we are ultimately only consulting our intuitions. Indeed, there seems nothing to stop me from claiming that while all of the following properties are *physically* dependent on other things, *having a sister*, *being in this exact location*, or *having weight Xkg* are all *metaphysically* independent of other things. If anyone disagrees there are no experiments we can use to determine which properties really are metaphysically independent, and the broad permissibility of the model makes it unhelpful for understanding real change, 'naturalness' or 'duplication'. Metaphysical independence tells us nothing about this world and, without addressing science, has no place in this study.

These competing intuitions come across in significant examples; for instance, in his 'Defining Intrinsic' (1998) written with Rae Langton, Lewis favours 'weak-law' intuitions—where laws can be altered or removed while preserving the phenomena—that a property like the shape of a star should be preserved as intrinsic (Langton and Lewis, p.337). If laws are weak and we consider only what is conceptually possible, then perhaps there are possible worlds where a star has its shape (if we can still call it 'shape' in such different worlds) intrinsically and independently of its surroundings. But if laws are strong (or we are simply concerned with *this* universe, as we indeed here are) and the star has its shape in virtue of the forces and other entities acting upon it, then its shape is not intrinsic.

Here again, I cannot see any way for a unique set of intrinsic properties to be universally agreed upon unless we adopt this latter caveat of nomic similarity, since otherwise we have no external standard with which to arbitrate disputes of intuition. Thus, I disagree with Lewis, and do not think that the intrinsic/extrinsic distinction should be a modal one. This is particularly so given my intention to integrate metaphysics with our best physics—to engage with this world—and to see whether the intrinsic/ extrinsic distinction is useful. The permissibility of metaphysical dependence throws out any refinement in definition by allowing almost any property to be intrinsic and degrading the related understanding of things like real change and naturalness. Such modal dependence is thus best suited for a metaphysics of possible worlds rather than the current focus on metaphysics in this world.

2.1.2 Causal

Causal dependence does *not* seem to be what Lewis meant by 'dependence' in his definition of intrinsic properties in section 1.2.4. However, it is a central notion of 'dependence' and one that has more teeth in analysing dependence claims in the known universe. Indeed, given the lack of traction with intrinsic properties as 'metaphysically independent', causal dependence seems like the obvious choice to test our definition of intrinsic. That is, one can define an intrinsic property as a property that does not *causally* depend on any other thing (either immediately or ultimately):

> (1) An object's property is intrinsic if it does not immediately[13] depend upon, or is caused by, any other thing.

This follows the traditional understanding of causation whereby, to say that x 'causes' y, or y is causally dependent on x is to say that whenever an event x occurs, a second event y must subsequently occur *ceteris paribus*. Under (1), dependence consists in what actually caused

[13] I appreciate that causation is notoriously difficult to define, but for the purposes at hand, this simplistic formulation will suffice.

an object to possess the properties it does. For example, my property *having hair of length X* was most immediately caused by my cutting it, and thus that property cannot be an intrinsic property because it depended, on something beyond the object possessing it (e.g. it depended on scissors and their application to the hair etc.). This use of dependence excludes all properties as intrinsic if they have been immediately brought about by something other than the object, which generally includes such properties as speed, momentum, direction, potential energy, shape etc. (e.g. an object's speed will depend on other objects directly interacting with it or indirectly interacting through force fields). Presumably however, it would preserve such properties as *spin* and *charge* for elementary particles, at least prima facie. The second form of causal dependence for intrinsicality can be understood as:

> (2) An object's property is intrinsic if it does not ultimately depend upon any other thing.

This allows for the existence of objects to depend upon one or more other objects at a given point in time, a dependence in which most objects in the universe appear to participate, making this a more exclusive criterion for grounding intrinsic properties. Thus, the colour of my eyes ultimately depends upon the eye colour of both my parents (as well as the visible spectrum of the observer) even though my eye colour does not presently have any *immediate* dependence on them since my eye colour is mine whether they exist or not (again, assuming a consistent electromagnetic spectrum for the observer). This allowance for a longer causal chain in the dependence relation may at first seem totally unwarranted, but there is a possibility that such a caveat would get at the initial cosmic properties that stand as good a chance as any at being intrinsic—in the fundamental, global sense—to the basic objects that possess them. If we were to take 'ultimately' back to the nascent universe where all fundamental constituents were newly formed, the properties in existence then might be good candidates for intrinsic properties.

By (2), then, the realm of intrinsic properties has shrunk to an extremely limited set since most objects owe the existence of their current properties to the existence of something else. We would be hard pressed to find anything that didn't *ultimately* depend on something else, but we might have some hope of finding properties that weren't so needy in the immediate causal chain. Thus, we could define an intrinsic property of an object as one that cannot immediately causally depend on anything other than that object. Prima facie, properties like *mass* and *charge* seem to persist solely by virtue of the object and remain whether the object is underwater or on a mountain. If those intrinsic properties vanish then so too does *that* object. For example, a clay statue will possess certain properties like *mass* that will persist when it is in a courtyard or on the moon but which disappear when dropped into a burning sulphur pool. The clay statue would then cease to be, along with *its* properties (the properties may of course persist but be attributed to other things, say, sulphur-clay lumps). The causal account also excludes obvious extrinsic properties like colour and smell, since they change with lighting, the surrounding medium and the characteristics of the observer. This account is more helpful and accessible than metaphysical dependence by fitting with both scientific talk and other familiar models of causation.

2.1.3 Constitutive

Roughly, the intuitive distinction between constitution and causation follows the distinction between the component parts of something and the chain of events that leads to a certain state of affairs, respectively. For instance, we might say that a particular chair was caused to exist by a chair maker—such that it causally depends upon the chair maker—but the chair, *now*, does not currently (constitutively) depend upon the chair maker for its various properties; the chair maker could vanish without *really* changing the chair. So, we might understand Lewis' definition of intrinsic properties as those that *do not depend in terms of their current composition* on any other thing. Constitutive dependence, then, is that which currently, at that instant, constitutes the possession of an object's properties:

> (3) An object's property is intrinsic if it does not constitutively (currently) depend upon any other thing[14].

Under this interpretation one might argue that my hair length is an intrinsic property because it does not *currently* depend on my cutting it—it just *is* that length however it came to be that length and whether I am at home or away or falling down a rabbit hole. This approach *seems* to preserve Lewis' example and *seems* to fit a metaphysical niche, but disentangling constitutive dependence from environmental interactions and causal dependence is not so obvious, and this example fails. Although we could adopt 'constitutive dependence' as our notion of dependence, I think it is merely a subspecies of causal dependence and therefore no better than the latter at picking out intrinsic properties.

[14] We may or may not wish to include non-material entities (e.g. spacetime) in this dependence claim.

That is, when enquiring after the causes of something being the way it is, we should exhaust all the information that could be gleaned from examining the constitution of something; what is commonly called constitutive dependence is simply current causal dependence (though the reverse is not true: not all causal dependence is constitutive). This can perhaps most easily be seen by comparing counterfactuals: although we might find it odd to say that the legs of a chair *cause* the chair to have various properties, we should agree that if the chair did not have legs, it would not have various properties. Similarly, although appropriately conjoined hemispheres could be said to constitute the property *being a sphere*, they can also be seen to cause that property; without hemispheres there would be no property *being a sphere*. Even though we can tease out some differences between constitution and causation, I do not think that they help us make sense of Lewis' definition of intrinsic properties since any sort of constitutive account was modally conceived and unhelpful to the current project

In looking at the dependence relations that constitute the whole (e.g. hemispheres constitute a sphere), we are not told which parts are intrinsic and why, but understood as a type of causation gives us leave to physically test the relations (rather than imagining metaphysical alternatives). Thus, my hair length is constituted by molecules, energy and a complex sea of interactions with the environment including (as noted) surrounding chemical bond strength, gravity etc. Speaking in terms of constitution does not let one ignore causal dependence, it only limits the causal chain under scrutiny, which at any given moment has a host of interactions and dependence relations with the environment. Not all causes for object properties are constitutive, but anything found to have constitutive dependence can be understood causally, even if it is simultaneous to the creation of the property itself; certainly it would strike us as a great aberration if a property were *not* to be causally dependent on something else. For example, the property *being a cat* constitutively depends on its cat parts. Some parts might support accidental or extrinsic properties, some might support intrinsic properties, but constitutive dependence is not a relationship that demarcates *which* properties fit into each category.

So although (3) may intuitively fit with Skow's and perhaps Lewis' idea of metaphysical independence—allowing the shape of sand to have constitutional independence—it does not seem able to do the desired work and collapses into a form of causal dependence. My height and shape depend for their constitution, causally depend, upon the surrounding, and indeed pervading gravitational field (e.g. I am in part constituted by this field and so will be taller on the moon than on Earth) such that my height always depends upon my environment. That is, if the environment is altered in this way both my hair length and shape will change. Thus, I do not see that constitutive dependence offers a significantly different or helpful take on dependence than that implied by causal dependence.

2.1.4 Dependence revised

To summarise, I have reviewed the best interpretations of 'dependence' featured in Lewis' definition of intrinsicality and argued that a notion of causal dependence was the most helpful and accessible to our current project. I do not see that claiming 'metaphysical dependence' delineates a specific set of intrinsic properties since it ignores all the objective physical restrictions on independent properties and appeals to our intuitions without any recourse to rigour. Turning to possible worlds is no more than a turn to intuition; but when giving examples of supposed intrinsic properties we turn to *science*—we suggest *mass*, *spin*, *charge*—so why not turn to science for corroboration that our definition fits the data? To imagine possible worlds where properties and laws are vastly different pushes us far beyond the limits of our knowledge and seems wholly unhelpful in attending to intrinsic properties *as we perceive them* (a theme I will turn to in the next section).

Further, although Lewis does not appear interested in causal dependence, I think that it a) is a clearer notion than metaphysical dependence and b) gives a rich philosophical lesson in the fundamental connectivity of our universe. I also think that, in the case of intrinsic properties, it is artificial and ultimately unhelpful to separate constitutive from causal dependence since I argue that the former collapses into the latter; it is really just a distinction between historical and something like simultaneous causation. Causal dependence—rooted in the physical universe—is the only appropriate sense of dependence for this study, concerned as it is with the intersection of modern physics and philosophy. It is here that we can gain a foothold to see how well the classical conception of an object, with its properties separated from the surroundings, holds up. With this in mind, I will review intrinsicality's second ancillary concept of duplication, arguing that it fails to pick out intrinsic properties.

2.2 Duplication

Analysing the properties of duplicates across possible worlds is portrayed as a valuable tool by Lewis, despite concerns of circularity (defining intrinsicality in terms of the duplicate and vice versa). He states that any perfect duplicate of a thing possesses the original's intrinsic properties regardless of environment, while its extrinsic properties may differ. This approach raises concerns however, as to whether it is viable for our current physics-oriented study of *this* universe, and indeed, whether it can provide any new insight into intrinsicality. I believe the approach fails in both respects, and conclude that this piece of Lewis' definition of intrinsicality is really an organisational tool, useful only *after* a definition of intrinsicality itself is established. In this, I argue that duplicates fail to determine which properties are intrinsic both because of their grounding in intuitions and the epistemic inaccessibility of the possible worlds they inhabit.

Physical situations deal with what is *physically* possible, what (to the best of our knowledge) would occur if an object were moved from, say, the Earth to Mars, or to the surface of the sun etc.; possible worlds deal with what is *conceptually* possible, with what we find conceivable however awkward the changes to natural law or material constitution in such worlds. Importantly, this latter type of possibility has many uses within philosophy,[15] but I do not think clarifying the intrinsic/extrinsic distinction is one of them. Intrinsicality's role in helping us understand duplication and worlds with a similar history is impotent in such a closed definitional circle. Since we do not all share intuitions, an external appeal is needed, which needs to be something decidedly more than each of us fabricating some world where something *very* like object *x* but lacks a certain property and then presenting the scenario to others saying 'see! It must be an intrinsic property'.

Additionally, to admit possible worlds into our search for intrinsic properties is to vastly expand and diversify the type of situations we need to be classifying over, to no apparent benefit. If I can work out all the *actual* dependence relations of a property, it does not appear obvious that I should further consult my *imagination* in deciding whether that property is intrinsic in our universe; my imagination will not determine which possible worlds are the relevant ones. Arguably that is just sloppy philosophy. Taking an object to a possible world and vaguely (a full account of the mechanics and particulars of substantially different possible worlds appears too complex) supplying a different causal history or different instantiation of laws offers only an insight into our intuitions about which worlds are

[15] And, indeed, many uses within science. The idealisation of a frictionless plane, for example, is among such concepts which we do not expect to see within this world, but which are nonetheless useful tools in evaluating and understanding the universe.

more like ours and which properties are environmentally alterable in what ways. It does not offer a clarification of physical law or material interactions.

Some examples may help to highlight the difficulties, although the details do not hang on these; rather, the following are meant to highlight competing intuitions which are not resolved through appeal to duplication or intrinsicality since they are defined in terms of each other. The general pattern is as follows: Say property X of object O is a candidate for an intrinsic property. Turning to duplicates in possible worlds, you and I decide whether we think property X is possessed by O duplicates. Say the property X is *having mass*. I think of a possible world where I claim a duplicate of O lacks the property *having mass*, leading me to declare that *having mass* is not an intrinsic property after all. But you think of the same world and conclude that it does not matter that what I called a duplicate of O lacks the property because it is *not* a duplicate of object O precisely *because* it lacks the property *having mass*. Since duplication and intrinsic properties are mutually defined, we are left at an impasse.

For instance, some philosophers appear comfortable suggesting possible worlds where electrons behave exactly as they do in our world (moving toward nearby protons, having 1/1800th their mass etc.) except that they have no charge. I may argue that what is intrinsic to them is preserved and thus charge is not intrinsic. But does this *stipulation* convince anyone? Moreover, could the contrary of such a claim be proved false? Looking at the duplicate relation given by Lewis does not seem any more enlightening, *since the duplication relation gives us nothing particular or concrete to work with*. We simply offer timid counterfactuals to see whether *we think* that a property of mine *ought* to persist despite significant changes to the environment. Do we alter the laws of physics to maintain intrinsic properties? We have already *stipulated* that it is a perfect duplicate in these distant worlds, but the difficulty lies in determining what this perfect duplicate is and what properties it possesses. That is, we have avoided the difficult part entirely.

Further, one may question whether properties like electric or magnetic fields—the manifestation of which can depend on one's frame of reference—are intrinsic properties of particles or certain objects and from what frame of reference they are to be attributed to objects. Can an altered mass be allowed—and by how much? For example, if we take mass to be an intrinsic property and one shared by all perfect duplicates, would we then deny that an electron travelling at 99.999% the speed of light is a duplicate of an electron travelling at

28% the speed of light because from a certain stationary perspective its mass appears significantly greater? What frame of reference is to be privileged when we view an object across possible worlds? Because there is no privileged frame in which to determine set properties, it is unclear whether we are to conclude that intrinsic properties are indeterminate or non-existent, but in neither case are our traditional intuitions secured. There does not seem to be a theory-neutral way to define intrinsicality using duplicates. Allowing any sort of room for duplicate variation means outlining the types of difference permitted, which is simply *stipulating* the intrinsic properties we had set out to discover.

2.2.1 The problem with possible world intuitions

The previous examples beg the question: how are we to know what is permissibly altered in our duplicate's properties to define their intrinsic ones? Is it more important that the same configuration and function are maintained, or is it better to maintain laws? Whichever way chosen reveals our intuition about intrinsicality—but does it reveal anything more? Arguably not. It is not so much that we cannot conjure up some explanation for how something is a duplicate of me *despite not having X* (because we certainly can do that, as the fascination with zombies makes evident), rather, it is that whatever you are willing to sacrifice is a matter of your intuition, your prejudice of what *really* counts as intrinsic. That is, neither philosophical reflection on duplicates nor on possible worlds will give us objective intrinsic properties.

Because worlds with different laws are so wholly beyond our experience, it is ineffective to speculate on the consequences of placing duplicates in such an environment, especially when we already have so many unknowns with the physical universe at hand. There does not appear to be an objective way of analysing possible world examples, nor do they appear to be able to tell us anything about the actual world (which is presumably our central enterprise). Beyond the epistemic concern of ever gaining knowledge of intrinsic properties through possible worlds, there is thus the additional concern that possible worlds cannot tell us about the properties of *this* world.

If there is a duplicate in a world that differs importantly from ours, one in which, say, there is no gravity and some other 'force' exists that makes everything look the same, some argue that it is not a duplicate at all. Indeed, it may make "no sense to speak of a natural kind, *e.g.* being an electron, independently of the laws which govern its behaviour… Therefore, to speak of a possible world with a different set of laws to ours necessarily entails speaking of a world containing different natural kinds" (Bigelow, Ellis and Lierse p.380-1). That is, we have good reason to suspect Lewis' weak-law intuitions and metaphysical permissibility yield a situation that does not address *this* world at all. If Bigelow, Ellis and Lierse are right, then we can only speak of duplicates in exceptionally similar worlds where the emphasis is on scientific continuity (e.g. same laws, particles, forces etc.). This is a valuable caution on the use of possible world duplicates, since even if we could knowingly describe the behaviour of 'duplicates' in alien environments, we should be wary of calling them 'duplicates' in principle. Such uncertainty concerning what counts as a duplicate prevents any clarification on which properties are intrinsic.

Given our particular interest in the concepts and connections in this universe, the introduction of inexact (i.e. having no set calculus, no mathematical means of testing altered values in energies, laws, densities etc., in short having nothing but our own intuitions) possible worlds as a tool to better understand *our* world seems controversial at best and at worst misses the point entirely; it does not make sense to allow more than a very limited range of *physically* (rather than conceptually) possible worlds into our search for the way things are. This caveat substantially restricts the analysis of duplicates to the history and extent of *our* universe, and should helpfully narrow the options considered. Further, to make any useful predictions or conclusions about what would happen to an object when placed in a certain situation, something more than daily philosophical intuition is needed, and the equations, relations and proportionalities of mathematics and physics seem a preferred option. This approach—along the same lines as the move toward *causal* dependence—offers a much more restricted and technical approach to duplicates than Lewis had in mind, but may offer the most productive way out of his explanatory circle.

Thus, as I have been at pains to show, the study of duplicates reduces to an exercise in our intuitions about what counts as intrinsic, as *we* decide whether duplicates in such-and-such a configuration and environment are really perfect duplicates and thus preserve intrinsic properties. Understanding what humans naively think is *possible* is interesting in its own right, but such exercises can hardly be assumed to carve reality up at the joints. Instead, we have A's intuition that the properties *having such-and-such a hair length, having memories of X*, and *possessing charge Y* are intrinsic, and B's intuitions that they are not. Our intuition has repeatedly been shown inadequate concerning modern science, and if discussions of duplicates do no more than showcase our intuitions, I suggest they be shelved for a more physically grounded metaphysics of intrinsicality[16].

2.3 Contraction and the Way an Object *Truly* is

Although Lewis arguably side-stepped the worries with contraction by claiming intrinsic properties are those that an object possess whether lonely *or* accompanied, it is worth taking a moment to see why just the former stipulation is troubling. The idea of total independence from externals through contraction has been offered—notably by (Vallentyne 1997)—as a means of clarifying intrinsicality (see section 1.2.4), but this claim is ill-attuned to modern physical theories and makes a dubious equivalence between how something is in itself and how something is alone in a universe of itself. Even assuming we could happily settle on an object's boundary, most objects do not remain impervious to their environment and so undergo changes in classical intrinsic properties (e.g. even protons are expected to decay). This being the case, how are we to separate objects from their environment as Lewis and Kim stipulate? Vallentyne's approach faces the same sort of difficulties as far-flung duplicates; as one contends with worlds very dissimilar from our own force-filled universe, we are left with fewer and fewer intrinsic properties as they vanish in the total isolation of a universe alone.

Barring the immense difficulty in accurately calculating how an object would be as a universe unto itself or where, exactly, its borders lie, there seem to be many issues with this 'force-free' account. It certainly dispenses with many of the traditionally useful properties whose local intrinsicality we might wish to discuss. That is, this approach does away with local intrinsicality and possibly all global intrinsic properties as we know and use them, and focuses on what properties a fundamental object possesses when it is removed from any natural setting and set in a make-believe world of isolation.

That is a very strange prospect indeed, and removed from Lewis' perfectly natural properties. But if we were to take a definition of intrinsic like the one Lewis adopts and discard any properties that depend partly on things external to the object, then we are left with a much smaller set of objects to examine in a very *un*natural way that severs them from the properties in which we are interested. We seem far more likely to hit on what an object is *truly* like by considering it in light of how it actually always is. It may be that Vallentyne's cosmic reduction is meant to halt at some specified material distance, or in such a way as to

[16] Further, examining what physics has to offer on the subject appears an important step to take before postulating the closeness and internal organisation of possible worlds.

preserve a thing's *essential* qualities, but much more needs to be said about how that is to be calculated, and what things in what relation are to be considered intrinsic or merely a necessary background to the object's examination.

We may find that the messy world of interactions with the object *in situ* is where 'intrinsic' properties are located, and though they may (substantially) change over time, such a placement is more accurately an expression of what the thing is like in itself[17]. This challenge turns most of the discussion of intrinsicality on its head, focusing not on what properties a thing has in total isolation but on what properties it really has in this universe. While such a focus may not adequately live up to expectations of intrinsicality, the pursuit of a perfectly closed system of one may not sufficiently align with the properties of our universe either.

This link between intrinsicality and the scientific idea of a closed system is tempting, but problematic in telling ways. For instance, we might think that argon gas in a lead box would possess properties intrinsic to that system regardless of the exterior conditions. Certainly, the placement of chairs around the room, or where I hang my coat *seems* not to affect the gas' behaviour at all. However, at a fundamental level (and thus in principle), this is not the case. The surrounding orientation of mass, charge, heat etc. will all minutely affect both the lead atoms and the contained argon atoms in ways that make the attribution of intrinsic properties challenging. Photons may behave differently, wave functions may be altered, momentum and temperature vary. We feel comfortable in discounting such effects at fairly macroscopic scales, but it is at best an approximation and should be treated as such.

I have critically looked at some of the key ancillary concepts in our definition of intrinsic properties (from section 1.2.4): dependence, duplication and contraction to how an object *truly* is, and found them unhelpful. Distinguishing an object—as it truly is and with all *its* independent properties —from its environment is philosophically challenging, both because physical properties are more inter*dependent* than they first appear, and because the common appeal to modal accounts relies on unarbitrated intuitions. Understanding intrinsic properties in terms of duplicates does not provide us with any examples or assure us that intrinsic properties are an accurate and helpful way to carve up reality given the mutual definition, so I will dismiss the concept. Contraction also gives us nothing concrete to work

[17] This approach may align with a dispositional properties framework, in that what is intrinsic to something may be how it interacts in certain circumstances (for example, electrons are attracted to sources of opposite charge).

with and leaves questions of dependence open for vastly unfamiliar states of affairs that again give us no insight into intrinsicality and likewise any of the roles it is meant to serve. Metaphysical dependence is too permissive to determine objective dependence relations for a metaphysics of this world, while constitutive dependence is merely a subspecies of causal dependence. From this philosophical vantage, I will next look at physics with its accounts of causal dependence to get a better grasp on the problems with our traditional account of intrinsicality, and the classically precise separation of object and environment that accompanied it.

CHAPTER 3: Physical Exempla

In the previous chapter we looked at several problematic philosophical components of Lewis' definition of intrinsic properties (again: 'the intrinsic properties of something depend only on that thing; whereas the extrinsic properties of something may depend, wholly or partly, on something else'). Here, I will pursue the problem of (causal) dependence through modern physics, taking a step back to see just how great a challenge it poses to the classical conception of objects and to the notion of intrinsic properties that we attach to them. In particular, I will be exploring whether traditional intrinsic properties like *mass* have any place in such a classification, as well as exploring several other elements of physics that make the precise formulation of object boundaries and the designation of any independent properties extremely difficult.

Here, I do not mean to claim that the physics broached in this paper is immutable or guaranteed—history has made such convictions embarrassing. But even if current physics is mistaken, the suggestions provide the possibility of a conceptual alternative, and given the healthy interaction between theories of physics and applied physics, that is a valuable thing to possess[18]. There is quite a bit of information thrust into this chapter, and given space constraints much of it is cursory, but I hope to get enough relevant physics on the table to support later discussions on the alternative options for conceiving objecthood and the intrinsic/extrinsic distinction. To this end I will examine a) the acquisition and variability of mass, b) object boundaries, c) virtual particles and fields, and d) the unintuitive transformations of relativity and spacetime—all of which give an image of a universe that is far more *interdependent* and connected than the classical conceptions of 'object' and 'intrinsic' allowed. In general, then, this chapter examines the physical *inter*dependence of most properties and the indefiniteness of classically distinct objects. I conclude that the classical model of objects and their intrinsic properties is more trouble than it is worth.

3.1 Mass

Mass is a favourite property among philosophers when speaking of intrinsic properties—readily pulled out as an example of what they mean by intrinsic, and often followed promptly

[18] There is an empirically derived concern that humans can never know the basic intrinsic properties, and thus building a metaphysics around them is misguided. Such epistemological worries are important, though they do not stop researchers from pushing through previous barriers and addressing the universe as if it is explicable.

with an 'etc' instead of further elaborations (Weatherson 2008) [19], which is why I shall focus on it in particular. If the poster child for an intrinsic property fails, we will have good cause to doubt the utility of the intrinsic/extrinsic distinction. Similar doubts may arise around would-be intrinsic properties like a particle's *charge*[20] or *spin*, which followers of standard quantum theory argue are indeterminate until measured; for if a particle has, in fact, a definite location and spin etc., then quantum mechanics is incomplete (Lange, p.261). Although these properties are not directly addressed here, the failure of mass to meet 'intrinsic' criteria as well as the current scientific approach give reasonable doubt to their status and challenges the rationale of intrinsic properties in general.

Modern physical theories dispute the 'intrinsic' classification of mass (and similar would-be fundamental properties) while offering an unexpected reconceptualisation of it as a property acquired through interactions with a certain field. Although mass is commonly seen as a property intrinsically possessed by many objects (local intrinsicality), what makes it seem like one of the globally significant properties is its believed specific and uniform possession by certain 'elementary' particles, a trait that is wholly lacking in biological organisms; while it may be intrinsic to certain objects that they *have mass*, the *specific* mass (e.g. 3kg) may or may not be intrinsic. For instance, my mass is something that constantly changes because of external and internal processes (e.g. gamma radiation, the heat I give off, sweat etc.), but we think of an electron's mass as being quite set. If a particle interaction were to produce a relatively large negatively charged mass, we would expect it to produce several electrons rather than one really massive electron. However, currently (and for several decades) the best candidate for the nature of mass is relational and *does not depend solely on the nature of the object that possesses it*.

It will first be useful to review what we mean by the term 'mass' before investigating how it arises[21]. Mass is generally interpreted in one of two ways, both of which are deemed equivalent through general relativity (in practice if not conceptually); either mass is the

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[19] David Denby includes 'mass' in examples of intrinsic properties, along with some more controversial—and under my account erroneous—examples: "redness, roundness and being 3kg are intrinsic" (Denby, p.1).

[20] It has been argued that elementary particle charges may have altered over time, whereby the extreme conditions of the very early universe could have seen neutrinos with charge that subsequently evolved into chargeless particles (Ignatiev and Joshi 1993). Additionally, though a now unpopular theory, physicist Richard Feynman (via Paul Dirac) suggested viewing anti-particles as their paired normal particles moving backward in time (Feynman 1949), thus allowing charge to be a matter of directional (perspective) interpretation. Less is known about spin, though it is still generally regarded as intrinsic to elementary particles.

[21] There is a long history of regarding mass as a theoretical concept rather than an observational ontological primitive; for a thorough discussion of approaches to mass see (Jammer 2000).

property of an object that resists changes in its motion (typically regarded as inertial mass or m_i), or it is the property of an object that determines the strength of its interaction with a gravitational field (gravitational mass or m_g)[22]. Given these definitions—and particularly the former—one might wonder what exactly counts as resisting changes to motion; might an object's mood, or surface area, or charge affect this resistance and thus be counted as 'mass'? Such flexibility in the term is not so strange as one might think, and indeed, the idea of 'electromagnetic mass' (as opposed to gravitational mass) has existed for over a hundred years since at least J. J. Thomson's writing of it in 1886 wherein he noted that the additional resistance to motion felt by a charged (as opposed to an uncharged) sphere was not due to normal friction but "must be due to an increase in the mass" (Thomson, p.230). That is, charged—and generally fast-moving—particles exhibit a greater mass than uncharged or stationary particles. Because electromagnetic flux lines are directional, this observation lead to the further refinements of 'longitudinal' and 'transverse' mass that could be observed depending on the direction of observation to the field.

Electromagnetic mass, however, like gravitational and inertial mass, fails to be intrinsic by our standards, since the mass of an object is tied to environmental interactions, most specifically with the surrounding field. Another commonly used concept is of 'invariant' or 'rest mass' which makes use of the energy/mass equivalence and denotes the total energy (including momentum) of a Lorentz-invariant system or object. Such an interpretation allows for positive invariant mass values even when examining a pair of 'massless' particles (e.g. photons). Distinct from this definition and the others, however, is the hypothesised and unmeasurable (González-Martín, p.1175) 'bare' mass (attributable as an intrinsic property to an object free of any fields and interactions), which is presumed to be zero (Jammer, p.35). It is perhaps this 'bare mass' that philosophers have in mind for an intrinsic property, since it is free of any environmental interactions, but such a formulation is arguably of little use since it is only hypothetical, requires a very unique and abnormal environment, and our predominant understanding of mass is as a relational property—as an environmental effect. Thus, I will refer to the empirically observed mass in the gravitational or inertial sense.

It is noteworthy that both these senses of the term are relational, that is, they depend upon how the object in question interacts with other entities. Looking to the mathematical

[22] Gravitational mass may be further divided into active (the gravitational force exerted by the body) and passive (the body's susceptibility to gravitational force), but the specifics are not important to our discussion.

formulation does not seem to be any different, as inertial mass (and thus equivalently m_g) can be defined, via Newton's second law of motion, as the ratio, or proportionality factor, between a force and its produced acceleration (f = *ma*). As physicist Max Jammer notes, this is not a very satisfying definition, as we are prompted to either take both force and mass as primitives, and thus have an *ignotum per ignotius*, or we also take the meaning of force from this relation and are left with a circular definition. If this is what we mean by mass, it is odd that it should so commonly be seen as an intrinsic property. We may then ask if, say, an electron were not interacting with *anything* would it possess its mass of roughly 1/1800th that of a proton[23]—or indeed, *any* mass at all? That is the question of intrinsics put to mass, and to which our best physical theories respond negatively.

If, on the other hand, we assume (as philosophers seem to do) that the object possesses this property of interaction even when not interacting, then we might again be driven toward developing a metaphysics of dispositions, whereby a particle has the intrinsic disposition to produce the phenomenon of mass when interacting in such-and-such a way. My focus here is not on dispositions (though more in 4.4), as I want to continue with the notion of properties at hand. For now, I will focus on non-dispositional intrinsic properties and pick up Bauer's mention of the mass-generating Higgs field.

With our definitions of mass, we can inquire just how particles get the masses they have. Researchers began creating the modern answer to this question some 50 years ago with the hypothesis of an all-pervasive field that ultimately became known as the Higgs field[24]. It is supposed that this is the field in virtue of which particles (and thus ourselves) acquire mass, and so will bear some investigation. Along with work by Peter Higgs, in the early 1960's Carl Brans and Robert Dicke suggested that Newton's gravitational constant *G* might vary over space and time. They calculated a new scalar field φ (later reconstituted as the Higgs field) which was inversely proportional to G, surmising that "any measurements of an object's mass would therefore depend on the local value of φ" (Kaiser, p.537)[25]. This Higgs

[23] Even to calculate a particle's mass, a renormalisation procedure is required; the emission and subsequent re-absorption of a photon by a bound electron leads to calculations of infinite self-mass (or energy) for the electron. To cancel out this infinity, the associated divergent energy shift is used, rendering a renormalization of mass (Jammer, p.39-40).

[24] While this approach has been common knowledge among physicists for generations, it has not appeared to come to the attention of many metaphysicians, or if it did, was deemed inconsequential.

[25] Specifically, particles of the gauge field would acquire a non-zero mass given by $m^2=2g^2v^2$, where g is the coupling constant determining field interaction strength and v is the velocity (Kaiser, p.539).

field[26] is a remnant of the turbulent start of our universe, uniformly pervading all of space like a giant net that at one stage embraced a symmetry among the particles (i.e. there were no separate forces and all energetic nodes—would-be particles—were treated the same). But as temperatures dropped and space expanded, the energy fluctuations of the field settled into a stable state that took a non-zero value and broke this symmetry spontaneously, interacting asymmetrically with particles. Indeed, researchers calculate that for space to be as stable as possible—to harbour as little energy as possible—the Higgs field will assume a *non-zero* value (Greene, 2004, p.260)[27].

That activity rather than immobility should be the most stable state may prompt us to wonder if interactions are not more fundamental and intrinsic to an object than 'being at rest'. This is a similar, if not identical, concern to my earlier worries that isolating objects from the rest of the universe à la Vallentyne may be a poor model for getting at their intrinsic properties. In both cases, the assumption I wish to challenge is that immobility and isolation are more accurate representations of objects (which are never in such situations) than how they actually are. The Kim/Lewis tradition of denoting intrinsic properties as those an object has *either* in isolation or accompanied is a more thoughtful step, but I'm not sure their reasoning was ever along the lines given above. I will return to the idea of interactive intrinsic properties in chapter 4, but for now we only need note that, though the exact way in which the Higgs field settles on its particular non-zero value is unclear, that it does so is critical for rendering mass.

Once the field has broken symmetry to assume such a value, the field's charge will manifest even when no particles are present, resulting in a weak charge pervading all of spacetime. The field presents resistance to less-energetic entities and accelerated motion. Thus, when particles responsive to the weak force acquire enough energy they are able to navigate the Higgs field as if symmetry were preserved and it had a zero value, that is, such particles are then able to interact as if they did not have mass (Randall, p.216). Relatedly, of the four fundamental forces[28], the Higgs field is most concerned with the weak force (and,

[26] The field also "can occasionally cause the spin to flip…[but] for a rapidly moving particle this happens only rarely" (Wilczek and Devine, p.243).
[27] It is conjectured that if the field gets trapped in a high-energy configuration, it will exert a negative pressure, which might account for the inflationary period following the big bang.
[28] The four forces are gravity, electromagnetic, strong and weak forces, though some have taken to shortening this list by combining the electromagnetic and weak into the electroweak force, and still others are confident enough to have only gravity and an amalgam of the other three.

indeed, has been called the ‘weak field’), giving the bosonic carriers of the weak force alone a ‘mass’ as opposed to the other forces’ massless bosons.

The massless photon is not perturbed by the Higgs field because it interacts only with electrically charged entities, and may thus pass through unscathed. In addition to the gauge bosons, the Higgs field also provides all non-force carrying fermionic particles with mass[29]. It is believed that these weak bosons as well as the fermionic “quarks and leptons acquire mass by bouncing off the Higgs charge distributed everywhere throughout spacetime. Without the Higgs field, these particles would also have zero mass” (Randall, p.214). And for the (brief) time the particles travel in between the ‘grid lines’ of the Higgs field, they would not have any mass at all. Admittedly, the charge of the field is spread so thinly throughout the vacuum (with a density roughly corresponding to 10^{-22} cm) that particles cannot travel freely over very long distances (Randall, p.214). Nonetheless, physicists argue that it is resistance to this field that creates what we call the property of mass, and without interactions with the Higgs field, “all fundamental particles would be like the photon and have no mass whatsoever” (Greene, 2004,p.263). Under theory, then, mass *is acquired through interaction* with the Higgs field and does not belong to a ‘particle’ in virtue of itself alone.

Beyond the constant acquisition of mass in interactions with the Higgs field, there are other strange effects that arise from ambient energy and within structured environments through the relations between particles that blur the concept of mass. For instance, the energetic ‘vacuum’ that becomes more noticeable with fewer particles around, can behave much like the Higgs field, in that “any particle placed in a jittery vacuum will suffer an enormous increase in its mass” (Susskind, p.249). Similar alterations crop up in the more structured environment of crystal lattices, wherein “electrons move around…as if they had a mass entirely different from their ordinary mass. Not only can this ‘effective’ mass differ from the free mass by factors of ten or even a hundred…it may assume different values in different directions, and…it may be negative” (Ridley, p.136). That the effective mass is different from that observed for a free electron is not so troubling (since the accelerations are quite different for each environment) as the allowance for negative mass, which is brought

[29] In quantum mechanics, particles are divided into Fermions and Bosons according to their ‘spins’. The former have half integer spin and include electrons, pions, muons, quarks and other matter constituents, while the latter have integer spin and are the carriers of the fundamental forces (via photons, gluons etc.).

about by the electron moving, in this case, “in a crystal in the direction opposite to that it would have in free space” (Jammer, p.38).

We do not typically think of mass as a quality that could be negative, but it is often this aspect that we forget in forming our expectations, divesting ourselves of the same reasoning that made negative charge and negative energy[30] palatable and instead focusing on mass as some sort of material essence. We seem more comfortable with the notion of negative *charge*—perhaps even negative energy—but is there a good reason for this preference? Physics suggests otherwise, using mass as an involved and interactive concept that takes account of its environment. For instance, it is not just the quantity of matter but the separation distance of objects, energy and pressure that contribute to the strength of the gravitational field (Greene, 2004, p.276), which in turn affects the mass. This is problematic for taking stock of mass as an intrinsic property; since general relativity tells us that any additional energy, in the form of pressure or otherwise, affects gravity—and thus our conception of mass—then a stretched rubber band is more massive than a relaxed band and a frog ready to jump is slightly more massive than it will be when sleeping. The addition of pressure[31] to our calculations (along with various concerns for properties like momentum) increases the complexity while highlighting the interactive and non-intrinsic nature of mass.

3.1.1 Conclusion

Mass has long been one of the few safe examples of an intrinsic property, as something that, unlike weight, does not depend on any externals, any other entity. Modern physics does not subscribe to this thesis, finding this bizarre world of properties to originate not from a “difference…of quality, or even of degree, but of environment” (Ridley, p.137). Physicist Bruce Shumm is likewise confident that “one of the most basic and common-sense attributes of a physical object – that of mass – has been removed from the conceptual lexicon by the juggernaut of modern physics, having been exposed as the combination of two illusory effects: those of internal mass-energy and of the Higgs field screening currents. The notion of mass, it would seem, is a sham” (Schumm, p.306). Even if our current theory on the nature of mass is faulty in some way, that physics operates within the framework that looks

[30] Because the full energy/mass relation is defined by $E^2= m^2c^4$, both the traditional positive root equation *and* the negative root equation ($E= -mc^2$) are possible, thus allowing for negative energy.

[31] Pressure need not always augment mass however, regional pressure may be negative, and thus exert a repulsive gravity.

for how fundamental particles *acquire* their mass suggests that the description of mass will revolve around interactions with external entities, and thus, traditionally extrinsic elements.

One might object that this is all too quick, and that regardless of the mess of interdependent properties there is still *some* property that distinguishes, say, electrons from photons; there is something, at base, that underpins electromagnetism over *here* and no-electromagnetism over *there*. While I am somewhat sympathetic to this approach, I do not think it is argument enough to counter my conclusions. First, there may be some physical difference between electrons and photons that *grounds* their different property manifestations, but we have no further idea what that is. Much like Kant noted of objects-in-themselves, we would not be able to say much more about them then that they may be there, which makes them far less useful to metaphysical debate. For instance, to speak of real change involves our stating, without any particulars, that *whatever* is really object X has not changed. The best we can do is say that there is something, we know not what exactly, that makes an object what it is, which is hardly an enlightening approach to understanding things like ‘naturalness’ or duplicate worlds.

Second, any relations between grounding properties or dependencies at such a level is equally mysterious such that there may be only one difference between, say, an electron and a photon that nonetheless gives rise to, or grounds—perhaps through interdependent means—what seems to us to be several intrinsic properties. That is, once we sacrifice the properties of which we have at least some knowledge (mass, spin, charge), we have no way of knowing what the underlying properties are, or how many there are. It may also be the case, however unpopular, that there are interdependent dispositions[32] all the way down (rather than distinct causal bases). That is, whatever makes properties or objects different from each other might itself be dependent on other factors. The range of unknowns attendant to these objections strikes me as overwhelmingly unhelpful, and though that certainly does not mean some form of underlying ‘intrinsic’ property does not exist, my argument is not so broad. My conclusions on metaphysical utility and the extensive growth in extrinsic properties from classical accounts are not in jeopardy, and moreover, intrinsic properties like *mass*, as we now conceive them, *are* dependent on things beyond the object in question.

If this is so, and environment proves so essential to an object’s properties, then the definition of intrinsic in 1.2.4 has a significantly deflated utility from its classical conception.

[32] For a discussion of dispositional intrinsic properties see section 4.4.

It gives us reason to doubt that the few other ventured 'intrinsic' fundamental properties (spin, charge) are wholly independent of the environment, or even whether we know where the environment ends and the object begins in order to ascertain this dependence. Although we might yet protest that there is *something* that underlies mass and makes particle A different from particle B, the environmental dependence of *mass* as we know it should be a telling example to complacent metaphysicians and pose a challenge to the real-world utility of the intrinsic/extrinsic distinction. With only a handful of tenuous property options in one half of the distinction, the distinction looks less and less useful and more like an antiquated world view that is more trouble than it is worth.

3.2 Object Boundaries

The next few sections (3.2 – 3.4) focus on issues of indefiniteness; boundaries are vague and the environment in which objects are immersed make classical ascriptions of object extent and characteristics indefinite. Our modern elementary particles are importantly different "from those of the atomists in antiquity by an absence of sharply defined limits that separate things being from things not being, matter from empty space" (Genz, p.216). Part of this difference lies in (a) modern particles' lack of sharp values *in principle* that we normally think bundle together in, or to make, an object (Davies and Gribbin, p.220), and part of the difference lies in (b) the particle's constant immersion and participation in energetic fields and dependence relations.

Indefinite boundaries have long been a concern for philosophers in all areas of vagueness, from language to the Sorites paradox, and these concerns can certainly be seen as an extension of those worries (e.g. just *where* does the object end and the environment begin?). But as noted in (a), there is a further conviction in these physical cases that the indefiniteness is there *in principle* and cannot be pinned to lazy language practices or inadequate measuring tools. This is a drastic break with the classical conception of an object and thus I will take some time to give an idea of just how large a break it is. In addition to this focus, I argue that this sort of vagueness of boundary is also significant to the *attribution* of intrinsic properties in at least two ways.

First, I take the classical conception of an object to assume a specificity of value and stability to its properties. That is, when something is described as *being coloured,* we expect it to be *some* colour in particular for some useful period of time; likewise if something has *mass*, we expect it to have some mass or other. The classical intrinsic property, then, is something that has more stability than an instantaneous flash and is determinate (and definite) rather than just a determinable. Physics gives us reasons to reject this and embrace property types, stopping short of specifying any definite property values. This may not seem like much of a loss (revisited in section 4.1), since even while there was an expectation of further definition we were happy to speak of intrinsic properties in terms of property types (e.g. speaking of *having mass* rather than *having mass of 3kg*), but the loss of 'definiteness in principle' needs to be noted.

Second, and more importantly, having indistinct object boundaries makes dependence relations indistinct as well, occluding a critical component of our working definition of intrinsicality. In struggling to separate our most basic entities from the environment, we are at best left with indefinite dependence relations, and likely often with simply dependent relations, both of which are problematic for determining intrinsic properties. Object properties that once appeared to be independent of anything else are now lobbed into a maelstrom of properties of the 'object-environment' system— not clearly possessed by one or the other.

Additionally, it is possible that fluctuating or indefinite boundaries will alter which properties are intrinsic to a given object at any given instant. It may be, for instance, that at one instant in *this* environment an object possesses property X while in another instant in *that* environment, the object lacks property X. Even if we somehow knew the fundamental global properties, we might still struggle with *attributing* intrinsic properties to certain objects. With 'intrinsicality' conceived of in terms of independence, the failure of classical objects to meet traditional standards of separation from the environment thus casts the attribution and existence of intrinsic properties into doubt. A serious engagement with our modern understanding of the relevant physics will go a long way in alleviating the anachronistic world view of sharp object boundaries in a mechanical, rather than quantum, universe.

3.2.1 Indefinite boundaries

One of the first concerns we might raise about the boundaries of objects like particles, is that they have vastly larger parameters than once thought, in the form of fields. In some sense, particles *are* fields; indeed, as Fleming and Butterfield have argued, it may not be particles 'at the bottom' at all, despite our common reference to them; further, "the single particle/antiparticle position operators are not independent constructions: their existence, and our study of them, in no way entails commitment to a particle theory as 'more fundamental' than quantized fields" (Fleming and Butterfield, p.153). To get an understanding of these particle-fields, physicists analyse data for 'sharp values' of the property in question (e.g. specific, determinate values for momentum, position etc.). One might think these sharp values are properties of the object *in virtue of itself alone*, but they appear to be extrinsic; "there is good reason to regard sharp values of properties as relational, as opposed to intrinsic attributes" (Brown, p.63)[33].

Part of the problem is that formulating a sharp value is done in terms of something else, some reference point. This then raises concerns involving relativity theory that make the needed relations to some other 'frame' body (rather than to an abstract coordinate grid) problematic, since in standard quantum mechanics the particle may not have a "sharp location relative to an inertial coordinate system or…to an external frame body, at the same instant" (Brown, p.66). The chosen spacetime slice, the system's reference points and how one classifies the system (e.g. as fields, particles or a mix of both) can all make a difference as to the values an object manifests. Thus, the lack of definite boundaries through 'particle-fields' and the relational nature of sharp values, makes the attribution of object boundaries and intrinsic properties (properties of *what*, *where*?) quite slippery.

Of course, particles are not just particle-fields, they are also particle/waves, and in either capacity their boundaries (because of their position) are fundamentally uncertain. Heisenberg's well known uncertainty principle clearly relates the uncertainty involved with our observational intrusion into the microscopic world, but it also reflects the dual nature of particles/waves. The physicist James Jeans argued that the electron, as a wave packet, does not appear to offer *both* an exact speed and position: when the wave packet is of an infinitesimal length it offers a fairly specific position but leaves no room for the wavelength qualities to develop, that is, there is not a clear speed. However, as the length of the wave packet grows, it becomes an infinite train of waves that gives no reason to locate the electron to any particular point of it (Jeans, p.168).

[33] Much more might (and has been) said on this, as many interpretations of quantum mechanics seek out relational schemes for properties, specifying "state-*dependent* rules for assigning sharp values to some of the self-adjoint operators [local observables] representing magnitudes (or equivalently for assigning bivalent truth values to some propositions describing properties of the system)" (Brown, p.61, emphasis added).

The exact nature and substance of this wave is elusive, and is commonly understood as a *probability* wave (much like a proverbial heat or crime wave). This energy or probability wave spreads out to infinity (Greene, 2004, p.90)—which of itself creates a problem for getting objects on their own away from any interactions so that we might observe their intrinsic properties—offering a range of locations that we might find the lump 'particle' at any moment and possessing articulate mathematical formulations to that end. However, the probability wave is most useful when examining many electrons; physicist Mark Silverman stresses that

> the manifestations of wave-like behavior are statistical in nature and *always* emerge from the collective outcome of many electron events. In the present [double slit] experiment nothing wave-like is discernible in the arrival of single electrons at the observation plane. It is only after the arrival of perhaps tens of thousands of electrons that a pattern *interpretable* as wave-like interference emerges (Silverman, p.9-10).

This probability wave may also offer one of the better options for an intrinsic property of these fundamental particle-waves (e.g. giving an intrinsic property of *probabilistic* momentum etc.), although trying to be much more specific than that may cause problems. Because the wave is probabilistic, accurate predictions of specific outcomes are impossible, leading many physicists to echo Jeans' comment on the built-in indeterminacy; "identical electrons in identical experiments may do different things. There is thus an intrinsic uncertainty in the subatomic world" (Davies and Gribbin, p.209). This also has repercussions for (b), separating the object from its environment.

3.2.2 Interdependent environment

To relegate this uncertainty to the quantum world alone would be over hasty and require explanation in any case. In principle this uncertainty plagues the human-sized world too, and as such gives an unabashedly interactive take on the configuration of objects as we know them. It may be that the very determinateness of visible objects issues from *interactions* with their environment, rather than external interactions merely degrading the object from its 'real' state. It is supposed that

> In principle, even macroscopic objects such as people and planets have their individual quantum waves…[but] the length of the waves diminishes in proportion to the momentum.…A typical bacterium would have a wavelength less than the size of

an atomic nucleus, and a pitched baseball has a wavelength of only 10^{-32} centimetres. Each of these objects can only tunnel through a barrier comparable in thickness to their respective wavelengths (Davies and Gribbin, p.207).

However finite it may be for familiar macroscopic objects, there is thus to be expected a blurring of boundaries as constituent particles occasionally tunnel into and out of objects and the objects themselves possess their own miniscule wave or 'mode'. This indeterminacy can generally be settled, often one property at a time, by an external entity interacting with the particle and forcing the so-called 'wave-collapse'[34], which happens countless times a second for large objects like chairs and people. The wave nature of the quantum realm means that probability waves interfere and decohere, which allows the 'fuzziness' and indeterminacy of the wave aspect to blur and collapse to a sharp value even when instigated non-locally. While admittedly happening in very short time frames, the blurring and collapse of an object's wave function (its decoherence) appears to thus *depend on environmental interactions* (Greene, 2004, p.210-11). Such dependence on things beyond the object itself puts its shape and the sharpness of it property values (and likely certain properties themselves) beyond the definition of intrinsicality given in section 1.2.4.

Thus, a cursory glance at delimiting an object's discrete extent with definite values reveals that mass, coherence and even the adopting of sharp property values depends on *other* entities. With the parent objects so fundamentally bound up and integrated with the environment, properties that we think stand a good chance of being intrinsic, have a high probability of likewise being integrated with and *dependent* on the environment. This situation is only aggravated by pervading fields that draw out virtual ephemera from what we call 'the particle' that seem neither wholly a part of it nor wholly separate.

3.3 Virtual Particles and Fields

Virtual particles and vacuum energy do little to alleviate this messy articulation of boundaries, either encouraging a grander ontology or a review of what may count as 'the object itself'. Pertinently, we may ask if it is the vacuum that elicits these virtual particles from the particle or the particle itself. And what *is* a virtual particle? Although neither answer is entirely clear, the latter may be slightly more accessible and so I will begin with it. A virtual particle exists for a *very* brief moment such that we could not, even in principle,

[34] 'So-called' because there is little agreement on what this entails, and whether writing it into equations is the most accurate interpretation of events.

measure it, and possesses all the properties except the exact energy of its modelled 'real' twin. For high-energy collisions or simply along the trajectory of fast moving particles, new particles and their anti-particles are created and "can be thought of as latent everywhere in space, as 'virtual' particles. Normally, virtual particles can exist only very transiently, because the Heisenberg uncertainty relation allows them to 'borrow' their rest-mass energy for only a very short time" (Begelman and Rees, p.225).

However, the virtual photon exchange (between electrons for example) can also occur over longer periods of time and over (relatively) vast distances, say, of a kilometre. This is permitted because "the energy of a photon can be as small as it likes. There is no limit because the rest-mass energy of the photon is zero" (Ridley, p.123). If the mass were greater, the distance would need to be greatly reduced such that the product of the energy and time would be within Planck's constant (h). The same sort of process can happen to a photon as well, allowing it to split into an electron-positron pair so long as it immediately recombines into a photon (although there is less flexibility for the distance and duration between absorption as both the produced virtual electron and virtual positron have mass). The image that emerges from this virtual world is of electrons surrounding

> themselves with a cloud of virtual photons…[and *these*] virtual photons may [in turn] surround themselves with virtual pairs…So an electron moves about in the centre of a cloud of photons *and* electron-positron pairs. Moreover, the [virtual] electrons…will be repelled electrostatically by their parent electron, whereas the positrons will be attracted…the electron has electrically polarized the vacuum! (Ridley, p.117).

It is this 'fuzz' that has moved scientists to designate quantum *fields* instead of merely quantum particles, embracing an uneasy ontology of field and particle revolving around calculations of probabilistic centres[35].

I think that this creates a problem of identity—an indefiniteness and ontological blurring between '*that* object right there', and 'this pervading energy type' (field). In perhaps something of a strained analogy, if one person became blurred with all of personhood on earth, we could expect a noticeable change in intrinsic properties. Whether your boundaries neatly follow your skin and hair, or whether they include a nearby dog and a flower vase will affect your identity and what properties 'you' possess. That is, what sort of

[35] Particles, then, are essentially part of the fields they contribute to and inhabit; some argue that they are "tied physically to the field and can never be considered as a separate entity" (Ridley, p.118).

physical parameters, interactions and sphere of dependence an object has, importantly defines that object; boundaries matter. So when we find a particle/wave or particle/field duality creating and annihilating in *immeasurable* times[36] particles of opposite charge, of varying spins and masses, we should at least pause and evaluate whether our classifications are as straightforward as we take them to be. Virtual particles may be persistent enough for us to wonder how they contribute to the object's boundaries.

The vacuum itself is a source of particles of all types, but interacts in specific ways with particles travelling through it to produce certain virtual particles. Indeed, the vacuum is not empty at all but is a huge reservoir of energy that can distort space, expanding it with a positive value or shrinking it with a negative one (Randall, p.298). While such quantum contributions seem to partly *depend* upon the energy of the vacuum, they are also important to the 'real' parent particle, since "the quantum contributions must be added to the classical mass to determine the true, physical mass" (Randall, p.246). With this connection to mass through the virtual particle formation around particles, part of the real particle's total mass lies in the area around the particle and extending to infinity (Ridley, p.134). Indeed, when looking at the fields generated around the quarks of neutrons and protons, "we find that the quarks themselves provide very little of the total mass and that the fields created by these particles contribute most of the energy…and, hence, the rest mass" (Krauss, p.70). The extraordinarily transient and directly unmeasurable virtual particles issuing from and collapsing into energetic 'space' thus significantly blur the object/environment distinction.

And these contributions not only affect mass but the strength of fundamental forces as well. Quantum mechanics calculates the strength of an interaction as the sum of interactions, or 'quantum contributions', that would occur from all possible paths[37] taken by a force-carrying gauge boson. For instance, the electromagnetic force decreases with distance because photons, which do not interact with each other, will encounter more and more virtual particles en route, diluting the initial electron's force as the photon's virtual positrons and virtual electrons polarize space. On the other hand, the strong force is *enhanced* over distances since its gauge boson, the gluon, *can* interact with itself and thus gives rise to a pair of virtual gluons (and so on) that enhance the strength over distances (Randall, p.232). These quantum contributions/ virtual particles seem far more natural to an object in the universe

[36] It is daunting to sift through the Planck length bursts of virtual particle formations and try to settle on a time *t* (or a spacetime slice) when the real particle is *truly* itself, replete with intrinsic properties.
[37] Taking the 'sum of all histories' is a standard approach in quantum theory and has lead to, among other things, the Many Worlds interpretation.

than static boundaries and, as I suggested earlier, motivate a much more dynamic notion of object and a rethinking of how and to what we apply intrinsic properties. Those who feel that the more traditional *examples* of intrinsic properties are more important to defining the term (e.g. mass), will need to seriously consider section 1.2.4's modal characterisation and defend its strengths against the interactive and interdependent picture science provides.

3.4 Relativity and Spacetime

The conclusions of relativity and the variability of spacetime are another concern for the separability of objects, and thereby attributions of intrinsicality, and while the difficulties they pose in this respect *might* be incorporated by using more refined expressions, or 'patching', of intrinsicality (e.g. taking into account the spacetime slice or the background temperature), they might simply confuse issues. The lack of an absolute reference frame makes a particle's 'real' intrinsic properties difficult to state absolutely and may even encourage an events-based rather than an object-based ontology whereby qualitative statistical centres are the fundamental stuff of the universe rather than particles or objects. As Simon Saunders has argued, "we think there is an essence, an underlying identity, which is there before us, rather than a particular event or sequence of events of such-and-such a kind. This is the picture that must be given up. Here as elsewhere relativity requires the language of events, not of things" (Saunders, p.93-4). To see why he might suggest such a metaphysical overhaul would require more space than presently allowed, so a brief overview will have to suffice.

We know that many of a particle's properties appear tied to its environment as well as to other particles, but included in this list is a particle's frame of reference, or how fast it is moving *relative* to other bodies, which can alter some of its most basic characteristics. For example, its size "cannot be meaningfully separated as a concept from the dynamic quantities energy and momentum" (Ridley, p.54). By factoring in momentum, one must examine the motion of a particle, which is bound up with its relation to other bodies (and how it is constantly changing position with regards to them), as it is unclear what motion would mean in a universe of one object. Motion is certainly an integral component to the characteristics of an object, but it is unclear whether it should be considered an intrinsic property or whether anything dependent on it should be. After all, it is defined by relations to something else (the earth or otherwise).

Because relativity theory disallows privileging any particular reference frame, there is no reason to suppose that a particle's mass at rest in one frame of reference is more fundamental than its mass at a high velocity or at rest in a different reference frame; mass (like the electromagnetic field) appears in different frames as different combinations of its energy and momentum (Lange, p.240). For instance, general relativity predicts that massive or rotating objects warp spacetime itself, and this *frame dragging* gives two very different perspectives when, say, an observer is falling toward a massive star. The falling observer will perceive himself falling straight down to the surface, while his starship crew, watching from a safe distance, will see him spiral down to the star in a curve (Greene, 2004, p.416). This sort of encounter will offer a different set of intrinsic properties depending on one's vantage point and can easily lead to calculations of mass exceeding the sum of the constituent masses (Lange, p.231).

Furthermore, the particle's inertial mass also "increases apparently without limit as the particle velocity approaches the speed of light…energy of motion manifests itself directly as increase of mass" (Ridley, p.105). Because of the viability of any reference frame (and the alteration to spacetime through object motion) this alteration of apparent mass and similar properties is not so easily discounted. Not only does this approach break with classical conceptions of an object, it has the potential to change even the property types of properties attributed to an object (e.g. *having mass* may disappear from some perspectives).

3.4.1 Temperature

Intrinsic properties are affected not only by their own interactions, but also by environmental *differences* to those values, notably through temperature and spatial density. As noted earlier, temperatures are closely tied to our conception of mass, in that, as temperatures increase, the Higgs field is predicted to vanish and particles will lose their mass. In addition to this change in the properties of matter, temperature (and thus energy, and even the size of the universe[38]) seems to be responsible for the variety of forces we have and the world as we know it. Thus, a possible world where temperatures are substantially increased would likely wreak havoc on our laws and ontology in a way that armchair philosophy has little chance of foreseeing. Physicists are confident that

[38] All these elements follow a related progression in our universe, where during its early moments it was quite small and quite hot and did not differentiate between bosons.

> the strengths of all three nongravitational forces depend on the energy and temperature of the environment in which the forces act…there is indirect theoretical and experimental evidence that at very high temperatures, such as occurred in the earliest moments of the universe, the strengths of all three forces converge, indicating, albeit indirectly, that all three forces themselves may fundamentally be unified, and appear distinct only at low energies and temperatures (Greene, 2004, p.526).

Trying to patch our attribution of an intrinsic property to include some specification of temperature will be one patch among many, and may require stipulating cosmological time as well, which looks to be more effort than it is worth.

While temperature certainly implies a strong temporal element in our intrinsic property calculations given its correlation to universal age (and how far back we want to take property dependence), pressure indicates the importance of spatial positioning. For even the life cycle of a star cannot be told without mention of its surroundings (indeed, it would be difficult to classify anything as an individuated object without some background from which to separate it), as the star's eventual implosion, and implosions in general, need pressure *differences* between places rather than simply high pressure (Begelman and Rees, p.229). Pressure of itself has no force and it is this relation to an *other*, to a substance of different density that allows the billions of stars and many other processes to continue. While large objects admittedly suffer little change in their important properties from their pressures, pressure is nonetheless "a source of gravity…[and] in the excited quantum vacuum…the pressure is so great that its gravitational effect actually exceeds that of its mass-energy" (Davies and Gribbin, p.165). This elevates spatial density differences to a very consequential plain in the quantum world, and makes it even harder to abide by the contraction and independence theories of intrinsicality posited in section 2.3.

3.5 Discussion

Let us take stock of our interlude with modern physics and review the physical challenges to the traditional 'object vs. environment' world view it presented. First, focusing on mass as an exemplar intrinsic property, we saw that mass not only has a fundamentally relational definition but that it is assumed to be something that is *dependent* upon the Higgs field. And because mass' definition lies with an object's relative resistance to motion, we saw that it is a property that appears to undergo drastic change depending on its environment (e.g. in crystal lattices or at high speeds). It seems clear that mass is not a property that depends only on the object that possess it—that the object has its mass in virtue of itself alone, and moreover is a property it would have independently of *any* other thing. This account does not bode well for the other candidates of the commonly proffered small set of intrinsic properties of say, spin and charge, (although *their* particular tenability is not dealt with here) and leaves the traditional separability of objects from their surroundings in jeopardy by highlighting a fundamentally interdependent world. Additionally, any move toward a more fundamental *something* that gives rise to properties like *mass* also seems lost in unknowns to such an extent that metaphysical discourse would receive more harm that help to include it (e.g. it does not enlighten the concepts of chapter 1).

Second, we looked at object boundaries through wave/particle duality, state-dependent sharp values and environmental decoherence. Standard quantum theory gives particles an inherent uncertainty in the values for their local observables (e.g. momentum) which suggests such entities may not have clear boundaries to be found. At the very least their nature is something much more exotic than our human-sized objects, and trying to dress such particles in the same sort of 'clothes' as chairs and cats is inappropriate. This is especially so when we investigate what our best theories say of how those familiar everyday objects *acquire* their seemingly determinate boundaries.

That is, generalising from the quantum world of single particles to the human-sized amalgamation of trillions and trillions of them, physicists argue that the particulars we see—all the properties and sharp values of position etc.—are produced through interactions with other entities 'collapsing' the wave functions to set values. The boundary between the particles that count as, say, 'outer cat fur particle', and the proximate but somehow distinct 'environmental particle' at a given instant may be indefinite, even in principle and thus presents a notion of 'object' distinct from classical conceptions as well as a fundamental hurdle for our attempted attribution of specified intrinsic properties. Furthermore, this interdependence of object properties with environmental properties at best makes the determination of intrinsic properties (as purely independent things) unclear and at worst leaves the classification without metaphysical merit.

Third, and relatedly, we reviewed the strange indeterminacy of object boundaries and property allocation surrounding virtual particles and the vacuum. From the continual and spontaneous production of particles—either from a real particle or the vacuum itself—we are lead to reject notions of an isolated discrete particle. At least currently, the constant fluctuations can seem to come from nothing at all, and while this may not be the case at deeper (yet unknown) levels of magnification, it has led physicists to remark that "even when no real particle is around, the field is gently, but persistently, bubbling with activity…the field indulges in virtual processes quite spontaneously! Everywhere in the universe the electromagnetic field is busy creating ghostly photons out of nothing and just as busily annihilating them" (Ridley, p.119). The inability to clearly define objects and clearly define upon what the nearby properties depend is an unhelpful approach to carving up the world (at least at microscopic levels) that should be replaced with more useful approaches.

Fourth, we briefly explored these concerns with relativistic spacetime slices and the effects of spacetime—as more than a mere background—on an object. Here, the lack of an absolute reference frame seemed to directly affect attempts at establishing an absolute delimiting of *an* object or a set of intrinsic properties, certainly as concerned the *particular* value of an intrinsic property (e.g. the property *having spin ½*, rather than just the property *having spin* simpliciter) and perhaps the property type as well. How an object moves and relative to what can affect the nature and possession of significant properties, and the interactions with its environment—simply through the density or shape or energy content of spacetime itself—can be critical to defining it as the object it is, rather than as the object it might be *if* the rest of the universe did not exist. The variation of spacetime thus offers no set footing for selecting the reference frame in which we can attribute the 'real' intrinsic properties to the 'real' object—much as the earlier reviewed indefiniteness of object boundaries prevented definite attributions of intrinsic properties—and the definition of section 1.2.4 cannot even get off the ground.

We might think intrinsicality doomed under its traditional model, or we might be tempted to continue 'waiting out the storm', and only weigh in when physics has cleanly and clearly settled on a fundamental ontology. But not only could that take centuries, it is less vibrant and, I suggest, less rigorous philosophy. It would be pleasing if our philosophical theories were robust against the uncertainties or incompleteness of physics[39], but in order to

[39] Although I cannot properly address it here, it is a rich topic to consider the *way* we access physical phenomena in regards to intrinsic properties. Kant, of course, counselled epistemic humility about knowing 'things in themselves', though there always seemed to be the underlying thought that despite their inaccessibility, there were, in fact, intrinsic properties. I see the interpretations of modern science as strongly weakening that conviction. The nature of how we study objects (and the microscopic in particular) is inherently relational, involving interactions with other objects of interest or with our own measuring apparatus, and this is

approach such a position, wherever the disciplines intersect, metaphysicians should benefit from working alongside current physics rather than in spite of it. And so it is with this appreciation for the dynamics and discoveries of modern physical theories as well as the philosophical misgivings concerning intrinsicality that the implications for the intrinsic/extrinsic distinction should be examined.

thought to be the case in principle: “not even nature herself knows how this uncertainty will resolve itself the next time the object makes its influence known, say, by the interaction with another object by way of one of the four forces” (Schumm, p.42). This sort of identity, however, does not entail identity of intrinsic properties, and thus, as Michael Esfeld puts it, “the natural sciences – the statements of laws of nature that they contain – tell us something only about the way in which things are related to each other” (Esfeld, p.8). If this is how we encounter the world, with no guarantee that our experiments yield intrinsic properties, then perhaps we ought to re-examine whether carving up reality into the intrinsic/extrinsic distinction is a good programme. It is worth pausing to reflect on whether intrinsicality makes good sense as a concept *for our world* and whether our inability to access it is more problematic than supposed. Moreover one might question whether such grounds are preferable for grounding our metaphysics upon.

CHAPTER 4: Alternatives and Conclusions

Taking the philosophical and physical concerns onboard, how might we reformulate intrinsicality? Section 1.2.4 characterised ‘intrinsic’ as a concept accessible through duplication and as a type of property that a thing possesses that is totally independent of any other thing. I argued that this was *philosophically* problematic because a) the nature of the intrinsic property’s independence is unclear and physically dubious, b) duplication does not tell us what is intrinsic, only what we can do with the distinction once we have it, and c) it is questionable that one should take intrinsic properties as those present when an object is in a universe unto itself. I also argued that the definition was *physically* problematic because i) interdependence predominates in the formation and allocation of properties, ii) the lack of distinct object boundaries hampers the clear attribution of dependence relations and intrinsic properties, and iii) relativity removes the idea of a preferred reference frame from which to locate an object’s intrinsic properties. Our difficulties, then, are in defining a distinct independent object and defining ‘intrinsic’ in a way that directly applies to our universe and gives useful guides for testing whether a certain property fits the definition.

I will outline what I see as the four most promising approaches to reformulating ‘intrinsic’, concluding that we should pursue a more relational, *in situ* account of properties and their interactions than the one given by the classical intrinsic/extrinsic distinction. One approach to characterising objects in modern physical terms might take the indeterminacy of quantum physics to prompt a reduction in the specificity of intrinsic properties to cover only qualities, rather than quantities. Or we might favour a reduction in the generality of our formulation of intrinsic properties to include a much more specific and strict criteria, a ‘patch up’ to include all the problematic variables (e.g. time, temperature, frame of reference etc.).

Similarly, the importance of systems and structures in the subatomic realm may suggest that *they* are the entities that possess intrinsic properties rather than mere objects. Many objects may be systems, but we do not think this of the fundamental objects, and the emphasis in describing something as a ‘system’ is on a connective network or structure rather than a distinctly bound and singular thing. We may also side with the concern raised in section 3.5 and decide that our inability, *in principle*, to discover intrinsic properties weighs in heavily on what we are confident to do with the distinction. Indeed, as physics finds the number and complexity of the calculations involved with integrated fields and systems to be much more vast and uncertain than the mechanistic calculations of classical physics, we may find that intrinsic properties have lost their utility.

With these concerns in mind, I will discuss several possible outcomes and effects of the re-conceptualisation of intrinsicality, looking at 1) its application to qualities and determinables, 2) a ‘strict’ specification, 3) intrinsicality as applied only to systems or structures, and 4) whether an interactive or dispositional formulation of intrinsicality makes sense. Far more might be said about the implications, but these topics should provide an overview of the issues for discussing what should be done with the intrinsic/extrinsic distinction in section 4.5. I conclude that 1) there are far fewer options for intrinsic properties than classically supposed, and, relatedly, 2) the traditional intrinsic/extrinsic distinction is more trouble than it is worth in metaphysics and should be jettisoned.

4.1 Qualities but not Quantities are Intrinsic (determinables but not determinates)

As noted earlier, we have a classical expectation that if something has a determinable property, say *having colour*, it will have a further determinate property, like *being red* (as taken from W.E. Johnson’s classic distinction). Where modern physics makes this untenable, we might try for an intermediate indeterminism. That is, it might prove more appropriate, and would certainly simplify things, if intrinsic properties ranged only over possession of a property rather than any specific or measurable amount of it, if, for instance, ‘intrinsic’ ranged only over determin*ables* and not determin*ates*. Similarly, we might distinguish between a quality, which we could say determines a mode of existence (e.g. *mass*, *momentum*), and a quantity, which further specifies the number or type of that quality (e.g. *12kg mass*). This approach easily accommodates the view (as argued by (Balashov 1999)) that even when not instantiating a property, the object may possess a zero-value of it. Under this view, that electrons possess the intrinsic property *mass* and photons do not is all we need say[40], so that it does not matter if the quantity of mass appears to fluctuate across different situations so long as the object still possesses *mass*.

Giving up on specifying information like ‘quantity’ in the formulation of an intrinsic property allows a more stable canon of simply qualified intrinsic properties. It would thus be a mistake to specify that something possesses the intrinsic property of *a mass of 12g*, perhaps

[40] At the subatomic level, fundamental properties are defined in terms of other fundamental properties (e.g. mass in terms of energy and momentum relations).

precisely *because* the context matters. This approach favours a type of local intrinsicality in that biological organisms and quarks are on equal footing in both possessing the intrinsic property *mass*; but it is their characteristic possessing of the property as well as its being a fundamental property (e.g. rather than the property *having hair*) that is important in a global sense. Indeed, many are happy to refer only to qualities in discussions of intrinsic properties and do not invoke the electron's particular mass or its unit of charge—perhaps because such properties are (seemingly unavoidably) defined *in relation* to other properties.

However, this approach does not really help the intrinsic/extrinsic distinction if we still find that determinable properties are dependent in some way (and reject Balashov's zero-value interpretation of properties). We might be able to dismiss the vagaries of an electron's mass in different contexts, but its having mass at all will still be a relational quality. Additionally, there may be challenges in securing the identities of the objects in question to ascertain whether and when they lose their 'intrinsic' properties (e.g. possess spin at time t_0 and then not possess it at time t_1), and thus we will be left with classifying which types of properties should be considered (and why), for which a return to physics would be in order.

Alternatively, we might take a 'qualitative approach' to encompass matters of degree such that properties are specified according to probabilities or by how closely they approximate a value. In this case, a particle's *spin* might be much more intrinsic than its location, perhaps because the spin is much more statistically applicable to it than its location. I certainly think there is something to be said for the degree approach (like Lewis' appeal to some properties being more natural than others). However, this also sounds like Lewis' mixed properties that are somehow not purely intrinsic or extrinsic (e.g. *being a cube that is accompanied by another cube*), and do not seem a particularly fruitful classification to preserve unless it leads to more significant reappraisals. It again seems confused to force such an old term like 'intrinsic' onto a new and fluid classification. It would not be the first time, however, that science persevered with a term in such a way (e.g. the 'atom'), and so this may offer a marginally satisfying compromise.

4.2 Strict specification (patch-up)

We may conclude that the difficulties in delineating an object and its intrinsic properties, are only difficulties and may be overcome by more rigorous specification methods that would result in intrinsic properties, however severely circumscribed. We may thus do a very particularised ‘patching’ of all the articulations of intrinsic properties to include a precise and diminutive time *t* with background temperature T and pressure *p* in a reference frame where object F is at rest’ that might capture all the exact properties of an object. Under this approach, we could not list the intrinsic properties of ‘an electron’, but only of ‘an electron of relative velocity v to frame of reference F at time t etc.’ so as to leave no room for physics’ complaints save for where inherent indeterminacy cannot be patched up. And where indeterminacy cannot be accounted for, we might happily accept the indeterminate property into our list of intrinsic properties in recognition of that aspect of nature. After all, we should not expect to do better than nature herself, and the discovery that a property is indeterminate in some way can be usefully incorporated into our discussions, leaving intrinsicality no worse off than any other branch of metaphysics.

This approach bears a similar onus as the previous in that, in addition to deciding upon a set of properties that count as intrinsic, we will need to gather a set of relevant specification criteria and give good reasons for it. In trying to give the salient variables for an electron in situation Z, we will need an analysis of the contributing factors that may always include certain elements—say, reference frames—and perhaps only a range of others—say, background temperatures between X and Y Celsius. Presumably physics will again need to be consulted for such a list, although if it proves too unwieldy, which seems likely, it is liable to be removed from metaphysical discussions; such specification , particularly to a time, is certainly at odds with the earlier desire for unencumbered intrinsic properties to pick out real change. As such, this approach may prove far too idealistic to be practically used or readily supported by both our intuitive notions of intrinsicality *and* our desire to give useful and significant metaphysical distinctions that follow physics’ lead. Indeed, this arguably presents intrinsic properties in such a constrained way that we may be doing the concept and ourselves a disservice. Whether the success of preserving intrinsicality is a real one, or whether its modification is more beneficial on the whole may be a topic for review, but I think such a salvage operation only highlights the disutility of such a term.

4.3 Intrinsic Properties of Systems

The substantial modifications to our traditional descriptions of an intrinsic property may prompt us to take several steps back and readjust our ontological lens to focus on systems—which may be ‘objects’ by another, modern, name—rather than capricious classical objects, so that what is intrinsic is intrinsic to some system (perhaps some physically vague region delimited only by a certain qualitative value range, e.g. ‘the region around a black hole that would absorb photons). Because of our difficulties in precisely separating objects we may opt for a seemingly less-exacting entity as that which possesses intrinsic properties. Physicist’s formulations of the behaviours and properties of minute objects are already overwhelmingly described by stochastic calculations, such that exact boundaries are less important than the *average centre* of mass or charge, or simply in terms of systems; for instance, “in general relativity, mass can only be defined globally. In other words, we think in terms of the mass of an entire system, enclosed in a figurative box, as measured from far, far away (from infinity, actually)” (Yau, p.59). It is appropriate, then, to follow suit and encourage a wider discourse of intrinsic properties as probabilistic or some other mathematical expressions delineating relevant systems—defined by statistical contributions to a certain value. One might thus try to pinpoint a system’s limits to the level of involvement of entities or quanta (perhaps within a given region of spacetime, or at certain intensities etc.) that expresses a majority influence from the forces, entities and interactions that designate the system.

Indeed, we seem compelled to this sort of conclusion in regards to fields, which are described by Ernst Cassirer as a system of effects rather than a thing; “from this system no individual element can be isolated and retained as permanent, as being ‘identical with itself’ through the course of time. The individual electron…‘exists’ only in its relation to the field, as a ‘singular location’ in it” (Cassirer, p.178). Although fields[41] are often taken to extend to infinity, the component forces and characteristics that make up the central and/or fundamental part of the system (e.g. the direction of movement, momentum, gravitational force, pressure change etc.) may be used to determine the limits of the system by their influence on entities. Thus, if, say, a particle responds to one of the central characteristics of the system rather than to any other system/entity exerting the same characteristics, then we can include it within the system.

It also seems reasonable that an entity may belong to several systems in different capacities, as it may respond to other forces (in other systems) that do not constitute the central characteristics of the system in question while still being a part of it. Intrinsic properties may be thus circumscribed under a sophisticated (if often statistical) model of physical systems, where some systems may be so small that they approximate traditional

[41] The ontological status of fields (usefully explored by Marc Lange) does not seem widely agreed upon however.

conceptions of an object, while other systems may extend throughout the universe. To implement this strategy effectively, we will still need to a) discern which things, if any, and which interactions[42] are free of influence from what appears to be their surroundings, b) establish satisfactory parameters for systems that reflect natural divisions, if possible, and c) consider whether it is appropriate to have intrinsic properties of just the system, or both the system and its parts. All of these requirements represent a good deal more research into the sufficiency of systems as the preferred bearers of intrinsic properties, but it offers at least the possibility of reconciliation between intuitions and physics.

Additionally, a systems-based approach may move us away from an 'object-centric' metaphysics to focus on the relations of the system as much as the relata. This in turn may damage such distinctions as that which we hold between objects and events. While the distinction is certainly useful in everyday terms, it may not be an appropriate distinction at a fundamental level, or at least, will require a very careful definition. We have already seen how the constant interplay of the minute physical constituents of entities with the surroundings leave an elusive (and at the quantum level seemingly necessarily indeterminate) boundary, which directly affects several criteria we use to separate the 'static and persisting object' from the relatively sudden interaction of an event. I do not claim this distinction to be of great significance in the metaphysical literature, but the change in interpretation is an important indication of a more general approach that focuses on the interactions and unfamiliar scales—a view that considers the implications of viewing objects as events. If intrinsic properties helped distinguish the object as a 'settled and structured persisting manipulatable thing', then perhaps with the rise of extrinsicality, objects may appear more like events in the system or structure of more inclusive things.

Of course, one might argue that, just as with objects, the interconnections between systems and their surroundings may make this approach no better off. Determining the intrinsic properties of a system, whether it be a rabbit or a microclimate, is exceptionally difficult, if not implausible, as, strictly speaking, they are not properly *closed* systems and have sometimes incalculable 'external' interactions that contribute to their fundamental constitution. From Edward Lorenz's influential reflections on the sensitivity of climate

[42] Behaviours may be no less fundamental or intrinsic than internal structures, although that seems to be a common supposition. Indeed, adopting a systems approach may encourage us to view the dispositions and interactions as more intrinsic than the properties attributable to an object in imagined isolation.

dynamics to the burgeoning growth of chaos theory[43], there has been an increasing awareness of unpredictability in how interdependent (intuitively extrinsic) systems and their constituents are; for instance, "in systems like the weather, sensitive dependence on initial conditions was an inescapable consequence of the way small scales intertwined with large" (Gleick, p.23). From this confusion surrounding complex dependencies, there appears a seemingly inevitable confusion about what properties count as intrinsic, given our working definition revolves around *independence* from other things. It is not enough that we know the rainfall in region *x* and the speed and direction of the wind at time *t*, we must also know the migration patterns of birds on the other side of the planet, or the position of the moon, or the onset of spring in Patagonia. These sorts of wide-ranging dependencies for a given property of an object again suggest 1) that there are far fewer intrinsic properties than classically supposed, and, relatedly, 2) the intrinsic/ extrinsic distinction is more trouble than it is worth.

4.3.1 Universal intrinsic properties

The push to find a closed system, free of influence from its surroundings, may lead us to a more radical reconceptualisation of systems intrinsicality that applies only to the largest, rather than the smallest things; that is, we might posit that only the largest of systems, the universe, has intrinsic properties,[44] embracing a monistic approach. Natural laws would then be intrinsic properties of the universe, as "laws neither ascribe properties to things within the world, nor describe correlations between things in the world. It is natural to construe them, rather, as characterizing not natural kinds within the world, but the world *as a whole*—as describing the kind of world in which we live" (Bigelow, Ellis and Lierse, p.384). Similarly, qualities like mass, acceleration and spin[45] may be taken as intrinsic properties of our universe, opposed to, for instance, the qualities *G*mass, *G*acceleration and *G*spin that might be intrinsic properties of a different universe. Under this view, objects might simply be the localised spatiotemporal expression of several intrinsic properties, and what we perceive as 'behaviours' might be re-categorised as internal structure.

This is akin to distributional properties like *being polka-dotted*, such that the universe can have properties located in some but not all regions, and further, that they could be inhomogeneous (something like the property *having lumpy mass*). Existence monists, who

[43] See James Gleick's Chaos (1987) for a good overview.
[44] Multiple universe theories may complicate this, depending on how the universes interacted.
[45] That these properties vary across the universe does not seem illogical; for instance, mass certainly varies across the spacetime region of an atom, with a dense nucleus and surrounding hair of electrons.

claim “that exactly one concrete object token exists (the One)” (Schaffer 2008) would presumably have to embrace such intrinsic properties. If there is only the One, then there are not the various chairs and cats whose intrinsic properties we need to worry about.

It may be that the correlated system is always a better candidate to possess intrinsic properties (in macroscopic realms as much as microscopic), or it may be that our desire for reduction has carried us past the point where entities can meaningfully possess intrinsic properties. This confusion about, or at least interchangeability of, objects and properties can be indicative of a lack of understanding or, more worryingly, a larger problem in our metaphysical project. Alternatively, it may simply prompt a readjustment in the attribution of intrinsic properties to systems, whose connection types or structural elements might more meaningfully exist if the ‘rest of the universe’ were taken away, or if the universe is all there is. I suggest that at least paying more attention to the systems approach will be useful in order to make a more robust account of intrinsicality.

4.3.2 Structural Realism

Closely allied to systems are structures, differentiated largely by approach as both comprise interdependent parts, though structures may be less of an active network than systems. Stewart Shapiro defines structures as “the abstract form of a system, highlighting the interrelationship among the objects, and ignoring any features of them that do not affect how they relate to other objects in the system” (Shapiro, p.74). There seems to be a greater readiness to ignore the haecceity of individuals in structural approaches, and this focus on structures is reflected in such theories as ontic structural realism (OSR) where the ontological primacy and even reality of objects gives way to the structure they inhabit. Under OSR, we might discuss the intrinsic properties of patterns and certain types of motion rather than the intrinsic properties of, say, a stone.

The exact formulation of OSR is unclear, not least because of its many permutations, but it gives a philosophical framework to many of the concerns voiced over the last century (notably from Kuhn) that “the permanent aspects of reality are not particular materials or structures but rather the possible forms of structures, and the rules for their transformation” (Wilczek and Devine, p.70). Indeed, structural realism was introduced by John Worrall as a more accurate model of theory change in the scientific realism debate, and has since taken on a life of its own, moving beyond its epistemological uses to modelling what actually exists.

Worrall argued that the progressive abandonment of theories maintained an important continuity of structure rather than content. Accordingly, our epistemic commitment should lie with the mathematical or structural aspect of scientific theories, rather than claiming to know the real furniture of the universe.

In their important overview of the subject, French, Rickles and Saatsi (2006) broadly characterise the modern structural approach as moving the fundamental ontology from objects to relational structures; "inasmuch as objects exist at all, they derive their properties and individuality from the relational network in which they are embedded" (French, Rickles and Saatsi, p.4). They argue that, really, the quantum world is made up of intersections, interactions and structural cohesion rather than objects. As with mathematics, the symbols themselves and their size or complexity is not the issue, but how they interact with the other system components, their structural role: "the property of inherent individuality that characterizes more complex, higher-level entities—such as a particular crystal in physics, or a particular cell in biology—is lost. Using some old philosophical terminology, I say that a level has been reached, at which the entities characterising this level posses *quiddity* but not *haecceity*" (French, Rickles and Saatsi, p.55-56). In other words, entities of different natural kinds exist (e.g. quarks, photons) but appear to lack unique individuality—and any haecceity they do possess is only by virtue of the structural relations they inhabit.

This focus on structure brings relations, rather than relata, to the fore, endorsing a long-standing suspicion held by the likes of Arthur Eddington: "in regard to the nature of things, this knowledge is only an empty shell—a form of symbols. It is knowledge of structural form and not knowledge of content" (Eddington, p.200). For OSR theories, then, the object's structural placement in the fundamental fabric (whatever that may be) is what is important, though beyond this general interpretation there is much disagreement. A brief overview of the main permutations of the OSR thesis will thus be helpful in reviewing what options are available for reformulating intrinsicality, in which I follow Ladyman's (Ladyman 2009) structure.

Under a more extreme interpretation of the thesis, our ontology shifts radically and only the relational structure itself is a candidate for possessing intrinsic properties:

[1] There are no individuals (but there is a relational structure).

This eliminativist formulation appears as one of the most counterintuitive interpretations of OSR, as it is not at all clear that one could discuss structure without the individuals that compose it. Assuming this is feasible and well motivated, we might then interpret this definition in one of two ways: first, we might focus on relations being of primary concern, with relations such as ‘beneath’ or ‘lighter than’. This places the formal relations, the principles, as more primary than the particular instantiation. Second, we might simply argue that individuals themselves *reduce* to relational structures, perhaps even that there is no fundamental level and it is relations all the way down[46].

In such an approach, arguing that there are no individuals does not mean we are necessarily getting rid of relata, rather we are stipulating that the relata cannot be individuals. Sceptics (e.g. Chakravartty 2003) have found this eliminativist idea non-sensical and applicable only to certain systems, as well as criticising its shortcomings in accounting for causation. But in support of the formulation, one might use mathematics as an example of such a structure, a scheme that relies on the patterns between imaginary points or place holders—the proportional distances between points that when repeated, subtracted, separated etc. yield other relations within the structure—perhaps without ever requiring a *real* entity to occupy the end points (or any points) of the section of pattern. What is intrinsic, then, is intrinsic not to an object but to a pattern, to the manipulations allowed or to the proportional relations of sub-structures.

A second interpretation of OSR focuses on the traditional notion of supervenience upon intrinsic properties by claiming that not all relations need supervene on intrinsic and spatiotemporal properties, and indeed, the dependence relation may go in the opposite direction:

> [2] Facts about the identity and diversity of objects are ontologically dependent on the relational structures of which they are a part.

In allowing the individuality of objects to be ontologically equivalent or dependent upon their larger relational structures, this view could allow more options for intrinsicality. We might still meaningfully speak of the intrinsic properties of objects while noting the intrinsic structural relations on which they may be dependent. This view (like most other OSR theories) redefines the traditional notion of a structure, which seems to follow a set theoretic

[46] See, for instance (Ladyman and Ross 2007).

model[47] whereby it is fundamentally composed of individuals and their local qualities (or intrinsic properties) on which everything else supervenes. Such a view of Humean supervenience has been challenged by interpretations of quantum theory, which argue that the world is not simply a collection of items existing independently of all the others where relations come second to the more fundamental relata. As Esfeld argues, at least "as far as quantum theory is concerned, there is no need for the correlated quantum systems to have intrinsic properties over and above the correlations in which they stand" (Esfeld, p.19). Thus, under this interpretation of OSR, a range or perhaps class hierarchy of intrinsic properties might be adopted, with a primary relational set and a secondary relata set. This classification may seem too complex, however, or simply open to the same concerns about the intrinsic properties of *objects*, such that one might prefer to eliminate intrinsic properties altogether.

If we are presented with a choice between preserving objects and preserving intrinsic properties in our metaphysics, many may be moved to reject the latter and give up on intrinsic properties for the fundamentals of physics (see 4.6). I think both classical conceptions require reformulation, but a less drastic compromise may be simply altering the intermediary notion of *individual* objects as those which possess intrinsic properties:

[3] Individual objects have no intrinsic natures.

On this account, quantum particles lack primitive thisness and are qualitatively identical to other members of their kind (e.g. electrons, pi mesons etc.). This lack of individuation[48] may prompt us to preserve intrinsic properties as properties attributable only to kinds, or universals rather than to individuals. For instance, it would be meaningless to speak of the intrinsic properties of an 'individual' electron; rather we might speak of the intrinsic properties of the electron class (or kind), of what it is to be an electron. Specific particles may be *numerically* distinct from other particles but the situation may so wholly determine the particular instantiation of that particle that it is constituted by its external structural relations and cannot be said to have intrinsic properties itself. This might be thought of as an intrinsicality of universals, focusing on the universals present in a given region or system and thereby relieving much of the pressure to distinguish an object and *its* intrinsic properties in a given context, although one may wonder how we justify the broader classification of the universal through such indistinct instantiations.

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[47] Although Jonathan Bain has advanced a category-theoretic account of OSR to this end (Bain 2011).
[48] Steven French and Michael Redhead have argued that either quantum particles are not individuals, or they are individuals via some empirically transcendent way (Ladyman 2007).

Under a similar account, traditional intrinsic properties are removed, but individual objects are allowed to remain and retain something particular to themselves, even if that something is a collection of relations:

> [4] There are individual entities but they don't have any *irreducible* intrinsic properties.

A close variant of [3], this view is most notably advanced by Michael Esfeld who argues for a moderate structural realism where all the properties of an object are relations to other objects. By allowing individuals to exist, Esfeld might respond to Russell's criticism—that to be anything at all things must be intrinsically something—by making the object's structural properties account for its intrinsic properties. Arguably, "how a thing can be a bundle of relational properties is no more – and no less – a problem than how it can be a bundle of intrinsic properties" (Esfeld, p.11). While this approach has the potential of salvaging the concept of an object and perhaps even that of intrinsic properties, it appears to reformulate intrinsicality *in terms of* relations (more of this in the following section). Indeed, this view looks like it is more concerned with what is *essential* to an object, rather than what is intrinsic, which seems a difficult concession.

Finally, we might find that the indeterminacy of objects moves us to take an instrumentalist or constructivist approach that rejects our epistemic access to objects and intrinsic properties:

> [5] Individual objects are constructs.

In this, objects and their properties have an instrumental role; they are useful tools for humans to orient themselves in the universe and help us make sense of structure, but there may *be* nothing that fits our conception of an object. While reaching a similar conclusion to [1] and [2], this approach gets there by different means and with its own further implications, whereby it is our epistemic claims that must be reformulated. This approach would presumably make intrinsic properties constructs as well, if they existed at all, but in this it rejects the scientific realist project (even if using its findings as support for its doctrine) and so is an aside to our current interests.

All of these permutations, however, are open to criticisms that the structure of an entity and its nature are not separate, and at the very least we cannot distinguish between theories about one and theories about the other. In which case, our attribution of intrinsic properties to structural relations may prove no better defined than to objects. If, however, we can meaningfully separate structure from nature or reinterpret them into a new holism, we may be encouraged to adopt a modification to intrinsic properties that applies to something more abstract than our definition of section 1.2.4.

4.4 Interactive or Dispositional Intrinsic Properties

Given the interactive and relational method of scientific experiment and the concerns raised in chapter 2 about defining intrinsic properties, we might try to negotiate a wholly new take on intrinsicality rooted in the typical ways an entity *interacts* rather than how it 'rests' in total isolation. Admittedly, this seems disconcertingly similar to extrinsic properties and is arguably in danger of making the intrinsic/extrinsic distinction no distinction at all. However, it might also be argued that *how* an object interacts to certain types of stimuli may be just as good a candidate for bearing the intrinsic moniker as would non-interactive properties[49]. Indeed, this may simply be the position of the dispositional essentialist (Bird 2005) that I mentioned earlier, arguing for an immense catalogue of intrinsic properties (or at least *powers*) made manifest only through interactions.

Although I think this approach has potential, I will briefly indicate why I think this route is problematic, though that is not to say it is insoluble. To maintain the intrinsic/extrinsic distinction in terms of dispositions seems undesirable, since even when cast as a disposition *mass* is either no different from other properties, or is extrinsic. That is, we do not acquire further tools to distinguish between intrinsic and extrinsic properties simply by switching to dispositional talk. For example, philosopher William Bauer argues that for the same reasons that weight is seen as an extrinsic disposition, mass also should be seen as an extrinsic disposition: for an object *x*,

> existing in a certain gravitational field activates *x*'s disposition to gain a specific weight. I suggest that if weight counts as extrinsically grounded due to the necessity of an object being situated in a gravitational field in order to have a specific weight, then this enhances the plausibility that mass is extrinsically grounded due to the necessity of a particle being situated in the Higgs field (Bauer, p.91).

[49] Even if we were to pursue this interactive framework, it is difficult to adequately define an intrinsic property, as, arguably, no *single* role (e.g. behaviour in such-and-such a circumstance) is sufficient to define it. So we are either left with a huge array of intrinsic properties, or with the task of narrowing it in some significant sense and focusing on a certain set of dispositions to represent the globally intrinsic properties.

I share Bauer's view and find dispositional intrinsic properties troubling. First, I dislike them because they seem to be applicable to *all* behaviour. To say 'I have the dispositional intrinsic property *disposed to have mass in such-and-such scenarios*' seems no different from saying 'I have the dispositional intrinsic property *being 3 metres from a sheep in such-and such scenarios*'. That is, they already look extrinsic and adopt the same model we employ for decidedly extrinsic properties (like weight). Second, I dislike the idea of dispositional intrinsic properties because we tend to formulate them (or should, given what we care about) in terms of what they will bring about *in conjunction with some other thing*. Unless we want to reduce dispositions to some configurational property of the object (e.g. *having energy arranged thusly*, which is fine but not dispositional), we are again constructing intrinsic properties along modal lines, and how they *would* be given certain extrinsic stimuli. Third, this approach gives us the framework to couch nearly *all* properties in intrinsic terms, which does not seem right; it does not help us distinguish between extrinsic and intrinsic properties.

Despite my misgivings, this view pleasingly parallels our experimental techniques that *seem* to leave us with only indirect knowledge of the thing in itself; as physics does the vast majority of its experimental work through interactive measurements, we have an epistemological gap whereby we learn about what exists through a thing's behaviour and actions, rather than by some direct and comprehensive knowledge acquisition of how things are in themselves. Our epistemological gap means that "the fundamental qualities we don't understand in themselves, and science can *never*, even in principle, learn what the ultimate causes are like in themselves" (Lange, p.80). If, however, we were to take the interactions, the disposition to behave in such-and-such a matter, as intrinsic, the epistemological gap narrows (if not completely vanishes).

Additionally, given that we expect fundamental particles to be without any parts (or microstructures on which we could pin the causal basis for a disposition), it seems then that their properties will be dispositional (Mumford 2006). While this approach may meet my concern that intrinsic properties should not be classified according to supposed instantiations in some possible world, it of course lies open to criticisms that the concept is so far removed from traditional intuitions that it is inappropriate to call it intrinsic. Certainly the indeterminacies surrounding object boundaries persist in this approach, but at the very least, it is useful in considering the role of interactions in how objects are constituted, which modern physics compels us to do.

To recapitulate, then, I briefly considered adjusting the specificity of 'intrinsic' by first focusing only on determinables and then embracing all the particulars in a patching attempt. Though neither cost seemed worth the unhelpful or unwieldy gain. I also looked at moving from an object-based property attribution to a systems-based one, with an allowance for probabilistic formulations. This seemed a promising way of dealing with some of the indeterminacy, and in this respect was similar to the structural approach looked at later, though both could use more work. Finally, I suggested reconceptualising intrinsic properties in terms of interactions or dispositions, which may get at how the object *really* is, but I think jars with our intuitive definition of 'intrinsic' in how it is formulated and in what utility it has. Even though all of these sketches are inconclusive about what to do with the intrinsic/extrinsic distinction, they all highlight the insufficiency of the current formulation.

4.5 What to do with the distinction?

If the intrinsic/extrinsic distinction breaks down, what does that do? How we choose to interpret the distinction is important for several areas of metaphysics, including defining duplicates, tracking changes, revealing fundamental properties, as well as with laws and causation. However, the intrinsic/extrinsic disintegration may do very little, simply excusing itself from the configurations of future metaphysics or taking on a different definition. Then again, it may encourage a much more radical understanding of our world—of the way things interact and our conception of property possession; in a somewhat Machian fashion, it may be that for something to be a certain way is for other things to be a certain way. That is, it may be part of a new interdependent and holistic approach to the systems, structures and movement of energy that constitutes our universe.

Intrinsicality goes to the heart of metaphysics by giving us a tool with which to carve up reality, to define its primitive components and understand what there is and how it interacts. It used to appear that we could isolate some thing, an object or property, and abstract it into an idealised realm for analysis. In this realm we could manipulate and test it and discover its particular properties, how it was in itself alone, and when we were finished we could put it back *in situ* with this new understanding preserved. But this is no obvious undertaking; abstracting objects away from the rest of the universe can drastically change their character while manipulating them in abstracted foreign surroundings can result in even more bizarre property manifestations that seem to fall well clear of our intuitions and speculative knowledge. This suggests that our approach of looking at the world in terms of objects, events and forces is outdated, unhelpful and likely erroneous. In losing the traditional intrinsic/extrinsic distinction we seem left with three options.

> 1) Keep the traditional distinction and define the vast majority (possibly all) of properties as extrinsic.

We may decide that our interpretation of intrinsicality is fine and accept all the challenges of physics, to acknowledge that there are simply fewer properties that meet its definition than once thought. Thus, where properties have any immediate causal dependence on seemingly external entities, the properties are extrinsic. What might this mean for philosophy? At base it means that what a thing is, in itself and on its own is not much. Lonely objects are exotic creatures and we should not expect them to be accessible to our intuitions. When discussing the more familiar zoo of properties, we might resort to creating new subsets or degrees of extrinsic properties to better capture characteristics we wish to discuss, turning to more dynamic models of properties. On the other hand we may start avoiding talking about things in themselves and instead follow structural realist approaches to viewing a world of connections, which are more important than any leftover properties of an isolated object. In practice, then, this action is similar to removing the intrinsic/extrinsic distinction.

> 2) Abolish the distinction altogether; the merit of the distinction rested on the intuitiveness of the classical examples which now appear mistaken.

In a more radical approach we could remove the distinction entirely, as an outdated classification that is doing us a disservice. Following Dennett in his rejection of the term 'qualia', we might replace it with 'intrinsicality' and proclaim that it

> is not just that the various technical or theoretical concepts of [intrinsicality]…are vague or equivocal, but that the source concept, the 'pretheoretical' notion of which the former are presumed to be refinements, is so thoroughly confused that even if we undertook to salvage some 'lowest common denominator' from the theoreticians' proposals, any acceptable version would have to be so radically unlike the ill-formed notions that are commonly appealed to that it would be tactically obtuse—not to say Pickwickian—to cling to the term (Dennett 1993, p.382-3).

Indeed, taking the loss of intrinsic to heart, one might side with some physicists and suggest a much broader reorganisation of properties in general, arguing that "the classical notion of a property is inappropriate to quantum theory….A quantum measurement should be regarded neither as revealing a property of the system nor as creating that property" (Hughes, p.302). Something along these lines will need to be considered, as the notion of intrinsic went hand-in-hand with classical conceptions of clean objects in the familiar world, and one might argue that with the diminution of that conception intrinsicality loses its significance. Indeed, the parameters it set and the intuitions it bolstered are really just cleverly disguised anthropocentric views of the universe.

It is not the minute particles or the interplay of massive conglomerations of matter that are the rare and exotic phenomena; *our human* world is the rare and exotic phenomena perceived through very rare and environmentally grounded observers. The bias that our observed world of chair-sized 'objects' and 70mph trains (with our negligible quantum waves and relativistic blurs) is the only world of consequence needs to be removed, and perhaps like geocentrism the notion of intrinsicality is simply another hallmark of its decline. This move may also make us embrace a more holistic outlook with an ontology that focused on connections and 'behaviour types' rather than location and 'object types' with their attendant intrinsic properties.

(3) Hold on to some form of the distinction, but give it different parameters and definitions.

If we would rather not have most properties collapse into extrinsicality or throw out the distinction entirely, we can attempt a compromise. We might take the criticisms on board and try to give an updated account of intrinsicality that preserves something of our intuitions while accommodating physics. In this I think it may be feasible to redefine intrinsic in terms of systems or structures, or to have different contexts of description for intrinsicality, used either for the more unfamiliar phenomena or for the common everyday world. Indeed, it may be that following its different usage in other areas of philosophy (e.g. value theory), we articulate a wholly different species of intrinsicality for biological, abstract or emergent entities. Or it may be that we turn intrinsicality into a matter of degree, a mathematical limit toward which properties tend by meeting certain criteria. I suspect that we could comfortably accommodate this contextual approach in much the same way we still use Newtonian mechanics rather than the more accurate Einsteinian mechanics for practical computations. But along the same lines, we need to take note of the technical distinction and should be more open to alternative approaches that do not privilege a bunch of individuals that come together, rather than a cohesive system.

Of these I think (1) is the least helpful, though perhaps an important first step, while (3) is the most likely. I favour (2), abolishing the distinction to look toward more interactive theories for further information. With so many properties appearing to extend off toward infinity from an energetic nucleus (or ‘object’) and bound up with the surrounding properties, holding on to the intrinsic/extrinsic distinction is simply part of the leftover furniture from an outdated worldview. To try and maintain (1), the distinction as it now stands with science pushing nearly all (if not all) properties into the extrinsic half of the distinction, leaves exceptionally little to work with and hampers the philosophical exploration of more dynamic models that could better adhere to physics. To try (3), holding on to the distinction but giving it different parameters (perhaps along the lines of earlier suggestions), is perhaps tempting, but again ultimately onerous. If we find old classifications unfit, we should at least have a go at formulating new and more appropriate ones than gerrymandering the old ones. Regardless of what changes we employ, I conclude that changes are needed—there are far fewer intrinsic properties than classically conceived and the distinction is more hindrance than help to metaphysics.

4.6 Conclusion

Some familiar properties may survive the challenges of modern physics, but it is unclear how many such properties there are and how best we might go about defining them. I have argued that it is unhelpful here to employ the contraction approach and try to account for the particular physics that would result in a universe made entirely with a single object (e.g. could we know that it would be sufficiently static etc. for our thought experiment to work?). I also argued that without turning to physics as an arbiter of dependence relations and as a guide to our world’s metaphysics, we seem to be left with a human-tailored abstraction of what *we* wish to call intrinsic. We simply choose an ‘object’, call certain properties ‘sufficiently’ and comfortably reflect on our ‘good enough’ abstraction, but this is not a coherent approach given our expectations of other properties and should be discarded as it is more trouble than it is worth.

Many of the problems with intrinsicality in physics arise from indefinite and inconstant boundaries of objects. In a world of such interconnections what questions should we be asking? With persistent boundaries gone we may look to statistical centres instead—not finding a discrete electron but the probabilistic centre of certain energy fluctuations. Arguably, the line separating bodies (internal from external) is a scientific convention not built into the universe. The fluctuations of these 'objects' reveal the problem of separating their structures, properties, and dependence relations from their environment. The clean mechanical motion and clear divisions of Classical physics may have thus unnaturally preserved the notions of 'object' and 'intrinsic' into a world of quantum fluctuations, and we need to mould our conception to match our changing world view. The challenges and alternative approaches offered by physics invite a more interchangeable account of 'object' and 'environment' that is not so strictly classified, with more emphasis on the interactions and characteristics of the whole than in its supposedly isolated parts, an interaction that will be more closely examined in Part II.

PART II: The Interface Between Objects and Space

In the previous Part, I argued that modern physics gives us reason to reject the classical conception of an object, comfortably separate from its environment with a small stable list of intrinsic properties. I have not proved that such a description fails to apply to *all* objects, since that is a pursuit appropriate for science in any case, but I hope to have made a case for moving beyond the intrinsic/ extrinsic distinction to find a more useful metaphysical device and to actively explore new models of objecthood. Having at first examined classical objects in themselves, I here examine models for the interaction between objects and space, with a focus on substantivalism.

Although this theory—along with its old rival relationalism—has received a good deal of attention over the years, I want to review the debate in light of physics and with the aim of again moving beyond such classical accounts to examine more interactive models. Substantivalism, despite its geometric success at scientific modelling, comes with the confusing philosophical baggage of substance dualism and a mathematical interpretation that, in some forms, encourages the reification of points. The Cartesian model of substance dualism has been criticised for its mysterious form of interaction, but comparatively little concern is raised over space-object substance dualism, and I think without good reason. The reification of points in some of the more mathematically compelling versions of substantivalism is a further point of concern given their supposed interaction with material extension, and part of the larger problem with interpreting mathematical formalism in many of these theories.

Substantivalism also struggles with various physical phenomena, either offering no account of it or dubiously (if not incoherently) modelling it. These problems need to be addressed by the substantivalist if the model, with its large ontology, is to remain viable. There are other theories, of course, like relationalism and supersubstantivalism that might offer a better fit, particularly as they avoid the mysterious ‘occupation relation’ and support the substance monism suggested by various physical phenomena. To examine the traditional model of space and object, I will first canvas the traditional debate between substantivalism and relationalism, along with the modern addition of supersubstantivalism, exploring the latter in slightly more detail and outlining some of the principal difficulties with Substantivalism. Second, I will look at physical phenomena that struggle to fit the substantival mould. Third, I will look at the theoretical challenge of making sense of location, or the ‘occupation relation’. Fourth, I will raise concerns on the reification of points (for both substantivalism and supersubstantivalism), and conclude 1) that substantivalism is inadequate in both its points-based and regions-based formulations and 2) monistic ontologies should be developed to take its place. Supersubstantivalism is one such theory, but the points-based formulation of it inherits several of substantivalism’s problems, leaving room for other singular ontological theories to address the issues. This offers the beginning of an attempted reconciliation between objects and space—a much more intimate reconciliation than is often assumed. I conclude with a rejection of substantivalism and an endorsement for other singular ontological theories (like dense relationalism).

CHAPTER 5: Relationalism, Substantivalism and Supersubstantivalism

The Newtonian and Leibnizian rival theories of substantivalism and relationalism, respectively, have doggedly persisted to the present, albeit with new physics to inform their arguments. Some, like (Belot 1999) claim that the general consensus among philosophers of physics is in favour of substantivalism—with its reified spacetime points—as that which best fits scientific practice. Indeed, “the intuitive feeling for Euclidean space has become so deeply ingrained in any trained physicist that it takes a real effort of imagination to identify precisely the actual evidence” (Barbour, 1982, p.265). There are persistent problems with substantivalism, however, that still make relationalism appealing, not least of all the former’s reliance on points. I will review these theories and consider the merits of the newer supersubstantivalist approach. Given the discoveries of quantum theory, the assumptions embodied by the classical versions of these theories need to be reviewed, and perhaps reclassified as unwarranted metaphysical prejudices. I conclude with an endorsement of singular ontological theories that can develop to take substantivalism’s place.

5.1. Relationalism

Relationalism, broadly, argues for a basic ontology of material objects and the relations between them; in geometrical terms, relationalists use “physical geometry as describing the possible spatiotemporal relations between material bodies and events, actual and possible. On their view, the spatiotemporal relations between events are direct rather than being parasitic on the relations between underlying points” (Belot, p.4). Following a relationalist perspective, Patrick Suppes suggests conceiving of spacetime as the set of possible positions of bodies, such that space*time* is “the set of all possible trajectories of bodies” (Suppes, p.395). For him, the points in spacetime are akin to the possible sequences of flipping a coin, as they have no concrete existence save for the one actualised sequence (i.e. the set of occupied spacetime points). Making objects primary in this way is appealing both to pre-theoretic empirical accounts of what exists and to the parsimonious metaphysician, but it is also appealing because of the problems it can avoid (such as the notorious hole argument discussed below). The familiar conceptual framework was advanced by Descartes[50], Leibniz and Mach and taken up again in modern discussions prominently by Gordon Belot and in (Barbour and Bertotti 1982) and (Pooley and Brown 2001), where it continues to find relevant subject matter in areas like quantum gravity (Belot 1999).

Reasons for endorsing relationalism include its parsimony, pretheoretical appeal, and ability to account for various models of spacetime (in the works of those above). The relationalist account also usefully revealed through discussions of object motion, which is generally described by the altered set of distance relationships an object bears to its surrounding objects. In such accounts motion is not about moving 3 parsecs from the 'centre' of the universe, but about the "the transfer of one piece of matter or of one body, from the neighborhood of those bodies immediately contiguous to it and considered at rest, into the neighborhood of others" (Descartes, *Principles* II.25). Spacetime points do not exist, let alone share the same existential status as material bodies. Under this account, spacetime is "a means of expressing relations. The spatial relationships between material bodies are regarded as no more requiring the existence of a special physical substance called 'space' than the relationship between Englishmen requires a physical substance called 'citizenship'" (P.C.W. Davies, p.2).

For the relationalist, then, location can be seen as a relation not between an object and the spacetime region it occupies, but between an object and other objects. Thus, to locate electron β is to give an appropriate set of relations to nearby material objects. The directed distance vectors can be extrapolated from measurement theory, whereby the relation 'being five metres from X' is ascertained by the possibility of laying five measuring rods one metre in length end to end from the object to X. The relationalist need not be concerned with 'covering limits' across the arithmetic model of a spacetime array of points, nor with

[50] Descartes describes a relationalism of motion, but it is much less clear that he favoured a relationalism of ontology, and his theory of motion remains compatible with other substantivalist views (Skow, 2003).

determining the ‘occupies’ relation to those prolific number of points. But there is a significant cost to this freedom.

One might not choose to be a relationalist since there is a concern that they must deviate from the ontic commitments of common scientific discourse and seek to offer “some more extended theoretical basis for physics in which space-time points are constructions introduced by definition. Or again, some other relational structures (e.g. between events) might be found isomorphic to…our space-time systems” (Harrison, p.190). Such projects to support a relational framework have not yet proved satisfactory, though one of the more successful integrations of relationalism with physics was achieved through the work of (Barbour 1982). Here, he takes the dynamical relationalist view of the *universe as a whole*, made up of moving bodies, which is determined intrinsically to that system (and not relying on extrinsic references to points). That is, he looks at the whole of the universe in calculating the dynamics or characteristics of any one part, because it is *all* of the other bodies that determine any one value for *this* body here (Barbour, 1982, p.269-70). Employing such Machian principles to dynamic physics and field theory, Barbour claims to recover a range of equations from modern physics’ canon, including variational principles in general relativity and relativistic time (Barbour, 1982, p.273).

Philosophers like Oliver Pooley and Harvey Brown have found that such “theories are arguably more explanatory than their conventional rivals” (Pooley and Brown, p.185). Barbour’s approach seeks to account for what actually exists rather than what might, which can be seen as a disadvantage and certainly a limitation of applicability. But when it comes to such aspects as describing a universe with zero-angular momentum, Pooley and Brown even suggest that it is a predictive asset, given that all our observations thus far support it. Gordon Belot is more cautious, seeing relationalism’s inability to describe a universe with non-zero angular momentum as a point of concern; it may be only a fortuitous contingency that our universe appears to have such a property, and while it does not debilitate relationalism, perhaps it is a strength of substantivalist theories that they can embrace a greater range of contingencies (Belot, p.16-17). Although Belot finds no satisfactory relational scheme for relativistic spacetime, it may be that further success in relational interpretations can be achieved when more conclusive and comprehensive theories are developed, i.e. when relativity and quantum theory are given one overarching explanation. In the meantime, relationalism often gets rejected because of its more scientifically burdensome point-free language as well as its handling of modal properties.

That is, while the relationalist may agree with the substantivalist about the geometrical structure of the world, she will disagree and be more restrictive about its modal properties. Following Leibniz, the relationalist argues that when there is no difference in the set of relations between bodies (say, if everything moved 3 metres to the ‘left’), there is no difference at all. This is his well-known verificationist criterion of the principle of the identity of indiscernibles, which can be seen to challenge the substantivalist’s attribution of particular identities to indiscernible points. For the relationalist, it is not the conceivable range of geometric relations between two objects that matters but the range of relations available *given the geometry of the world in question*; the relationalist’s set of modal properties are limited to the particular distribution of objects in a given world. The possible options for the relationalist seem more exclusive than those for the substantivalist, and this difference has implications for the possibilities considered by physics:

> Substantivalists and relationalists disagree about how to count possibilities—where the relationalist sees a single possibility (particles with such and such relative distances) the substantivalist sees many (particles with such relative distances, embedded in Euclidean space in many different ways). Consequently, the two parties differ as to the structure of configuration space (Belot, p.38).

But relationalists may not find this difference very problematic as it is no charge against their account of the way the world *actually* is; after all, it is only a matter of *conceptual possibility*—a limiting of considered counterfactual situations (involving universal rotation for example)—where they are known to lack the interpretive framework that substantivalist theories can claim. While it is unclear just how damaging relationalism’s account of possibility is, it may yet provide a satisfactory account of the actual properties, locations and entities of our universe.

To give such an account in a way that conforms to the mathematical descriptions of physics will be important if it is to play a viable role in debates on the nature of spacetime and objects. I suggest that relationalism can be found to approximate the mathematical model by populating the universe with extended material bodies—the energetic minima of a discrete ‘spacetime’ now refashioned as material substance. Call it ‘dense relationalism’, which adopts a particularly dense distribution of minute material things (perhaps including the energy stored in the 'vacuum') that may even allow spacetime to be an emergent property; thus, dense relationalism might recognise a similar set of elements to a substantival point array and so better integrate itself with the account of modern physics. All non-zero values of fields could account for material objects, or further, one might then have Planck size (or whatever the object minima is found to be) oscillations of strings instead of points, which macroscopically approach the point-like particles of our calculations. As we will soon see, such density of material objects may also be seen to mirror the supersubstantivalist's identification of 'material objects' with spacetime points, only in this case it is the spacetime points used by physical *models* which are to be identified with real material objects. Indeed, it may be merely a semantic difference that separates the dense relationalist from a supersubstantivalist who associates objecthood with every region of spacetime.

Dense relationalism might also be a compelling model for suggestions that spacetime is an emergent property or other theories that place movement of *objects* at the centre of property formation. That is, it is difficult to view spacetime as a substance on par with matter if it only emerges from the interactions of objects, and so depends upon matter for its existence. While certainly not in the orthodox canon, it might be interpreted that fundamental accounts of the universe—such as superstring theory—rely on motion to explain properties rather than some static background array. For instance, 'charge' is defined as a particular type of vibration that responds in set ways to magnetic fields. This view recalls the primacy of interaction from the previous chapter and, if correct, would appear to pose an advantage for relationalists.

5.2 Substantivalism

Substantivalism, favoured by philosophers like John Earman, Graham Nerlich and Hud Hudson etc., argues for a fundamental ontology of material bodies *and* spacetime upon which the material bodies are pinned. Spacetime is typically conceived as points (points-based or pointy substantivalism), although it can also be a minima of regions (regions-based or regions substantivalism). The latter view is less common, but in both views, these points or regions exist in the same way as material bodies and are not reducible to them or events (Gilmore, p.1248). In other words, "the substantivalist thinks of a physical geometry as being comprised of points standing in relations to one another, and of the spatiotemporal relations between material objects and events as deriving from the relations between the points which they occupy" (Belot, p.34). Substantivalism, then, has a larger ontology than relationalism and an 'occupation' relation that holds between bodies and points. For Hud Hudson, such a model is preferable, and is described as "a concrete particular with an ontological status not reducible to relations between those material objects and events" (Hudson, p.97).

Reasons to be a substantivalist principally include the long tradition of scientific support, as both classical space and relativistic Minkowski spacetime "are composed of instantaneous, spatially unextended, mereologically simple spacetime points…[although] they differ with regard to the spatiotemporal relations that hold amongst their constituent points" (Gilmore, p.1225-6). Modern field theory also relies on the point model (with further topologies etc.) of reality, which takes its cue from mathematics, and has constituted remarkably successful theories that integrate mathematical and geometric models with material bodies (Earman, p.159). Having a substratum of points is additionally useful to explain the propagation of light, free fall, and acceleration (Hoefer, p.12), while Earman thinks substantivalists can also account for "the need to support the structures that define absolute motion, the need to support fields, and the need to ground the right/left distinction when parity conservation fails" (Earman, p.173)[51]. For many, the traditional Leibnizian concerns levelled at substantivalism (such as shifting all objects 3 metres to the left) do not seem compelling reasons for rejecting it compared to the utility in physics.

The ease with which our physical theories fit a substantivalist model may be a reason to commend it, but that certainly does not prove it is the case. Indeed, since the 1980s people have cited the 'hole argument' as a reason to reject substantivalism, or at least to greatly modify its 'naïve' formulation in terms of the manifold, as it presents a glaring break in the smooth fit between the implications of physics and those of substantivalism (Pooley and Brown 2001). The two central components of the general relativistic universe are the (at least four) dimensional manifold of events, and the metric field that specifies spatiotemporal distances between the events on the manifold. For the substantivalist who believes the manifold of spacetime points exist, with a variety of modal properties, independent of the metric (and therefore fields) applied, this creates a problem of indeterminacy.

[51] The failure of parity conservation refers to the 'directedness' of certain phenomena that, for instance, decay to the left with a greater likelihood than to the right.

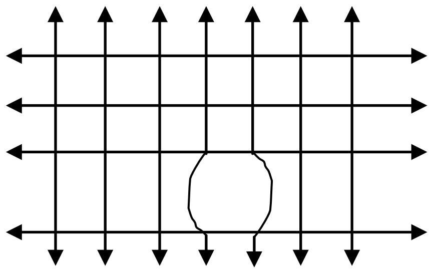

Figure 1. Spacetime metric with a ‘hole’ in it.

To see this, the hole argument uses the general covariance property (no in-built coordinates in nature) of general relativity (GR) to redistribute the same metric over different events. If we choose to redistribute only over a small region (the hole), we will be left with mathematically distinct regions that allow for spacetime trajectories to meet at different events (or points) within the hole. That is, the complete specification of spacetime enabled by GR is provided by the field equations and the distribution of a metric and stress-energy tensor across the manifold that nonetheless do not specify the distribution within a ‘hole’:

> given a complete specification of space-time and its contents (how the metric and stress-energy are distributed on the manifold) everywhere outside a compact region (“the hole”-not necessarily empty), this specification, together with the field equations, fails to determine how the metric and stress-energy fields will be distributed over the points inside the hole…If A is a space-time point that will (in fact) exist around here sometime tomorrow, the past plus the field equations do not determine whether A will underlie me, or you, or some part of a star in a distant galaxy (Hoefer, p.9).

Outside the hole there is observationally nothing to determine the properties within it; “the manifold substantivalist is committed to factual differences between the two spacetimes that are opaque [to] both the observation and to the determining power of the theory” (Norton, p.283). That is, it appears that substantivalism commits us to indeterminism (about which specific points will be connected with which events), which, most believe, is not a matter for philosophy but for physics to decide.

This problem spawned a range of responses to side-step the hole argument and replace simple manifold substantivalism with more sophisticated models. Many either argued that spacetimes with and without the hole represented the same state of affairs, or rejected the manifold as the sum of spacetime points, arguing that the metric be included as well (Pooley and Brown, p.184-5). Perhaps one of the more interesting examples is Carl Hoefer's rejection of the individuality of points and endorsement of a 'metric field substantivalism' that is not concerned with the above kind of observationally-inert indeterminism. In this he finds the real culprit behind the 'hole' debacle to be "the ascription of primitive identity to space-time points, [which] can and should be rejected" (Hoefer, p.11). Hoefer adopts Leibnizian equivalence, where two putatively different sets of indistinguishable points represent the same possible world. Thus, Hoefer is happy to go along with, say, talk of electron A and electron B interacting even though there would be no difference if their positions were reversed. Curiously, his account leads to the same conclusion, by his own admission, as Paul Teller's *relationalist* view that denies point haecceity and takes the metric field to be the set of possible object positions. This similarity raises concerns about the physical interpretation of models in general as well as the integrity of such a substantival formulation. If contorting substantivalism to fit scientific theory brings one closer to relationalism, we have good reason to doubt the utility and rationale of substance dualism.

Indeed, one could argue that giving a "sophisticated substantivalism…would require considerable ingenuity to construct…and if one were to accomplish this, one's reward would be to occupy a conceptual space already occupied by relationalism" (Belot and Earman, p.248). That is, in trying to get a handle on what exactly space is, we seem in danger of reverting to a singular ontology like relationalism. While it is not obvious that the hole argument can be evaded so easily, substantivalism's effective fit with modern physical theories means that it has been the most common framework within which theories of location are couched.

Although, metaphysicians tend to be more concerned with cashing out the possible ways objects can be located at these points (or regions) than with explaining exactly how the object interacts with (e.g. 'occupies') spacetime, i.e. giving a full account of the occupation relation. *If* we are to take substantivalist accounts as the best model for spacetime, then we should surely try to cash out the nature of its interaction with objects, and whether and how this interaction may vary. As it currently stands, however, substantivalism does not meet this, or several other, challenges and other theories should be explored. One response to describing this relation is to dissolve it altogether, by eliminating material bodies as a separate substance and embracing a single *super*substantivalist ontology.

5.3 Supersubstantivalism: the best of both worlds?

Supersubstantivalism argues for a fundamental ontology of spacetime alone, where ‘objects’ are identified with these 1) points or 2) regions (with points-based and regions-based versions). That is, all material objects are identical to the region of spacetime that they occupy, and “space is the only first-order substance in the sense that space points or regions are the only elements of the domains of the intended models of the physical world” (Earman, p.115). Much like relationalism, this view has the advantage of parsimony over substantivalism, reducing the latter’s dualistic ontology to a metaphysics of spacetime points/regions and their properties only. Beyond this consensus there are several varieties—though few stated proponents beyond Jonathan Schaffer—that give varying emphasis to the relations and properties of spacetime regions.

On the extreme view of supersubstantivalism, simply the geometrical structure—confining terminology to points, lines, vectors etc.—of spacetime can account for all the objects and history of the universe, such that the model of explaining gravity in terms of curvature is expanded to cover all forces and particles (referred to as geometrodynamics). However, this project has not been achieved and is thought empirically inadequate by many (Schaffer, 2009, p.134). The more moderate view of supersubstantivalism (SS) preserves the non-geometrical properties thought to be instantiated by fundamental particles and simply makes regions of spacetime the bearers of these properties. Thus, certain regions of spacetime become ‘particle-like’ or ‘mass-like’, and manifest properties in such a way as to become ‘blue whale-like’, or in Schaffer’s terms—it allows the fundamental properties to be pinned directly onto spacetime. This more common view is the one I shall be addressing as SS, as it is much more easily made to fit with the current understanding we have of the universe.

There are positive reasons for endorsing this view of spacetime, often as natural extensions of interpretations of theories like GR in which “spacetime and things interact in a much deeper way than ever before…powerfully suggest[ing] a picture in which things are parts of spacetime” (Nerlich, 1994, p.208). Indeed there is an increasingly popular supersubstantivalist approach that endows space with all the properties of objects: “as we currently view things, matter or particles sitting (or moving) in a space are actually part of that space or, more precisely, spacetime” (Yau, p.19). It is because of such merits and its relative newness to the debate that I wish to give a more in-depth discussion of SS than was given with the more familiar positions of substantivalism and relationalism. To this end, the literature often begins tentatively by noting the lack of reasons *against* supporting such a view. Physicists and philosophers have both pointed out the conventionalism of science, as an accident of history, that may unfairly focus on only one approach, but as John Wheeler and Edwin Taylor observe, such conventional practice need not prohibit alternative interpretations.

> The best current thinking does not claim that particles are *not* built out of spacetime….For the time being, as a means to get on with the world's work, and to deal with particles on a practical working basis, it makes sense to *treat* particles as if they are foreign objects. This working procedure does not exclude any longer-term possibility to account for a particle in terms of geometry—as one today accounts for the eye of a hurricane in terms of aerodynamics, and the throat of a whirlpool in terms of hydrodynamics (Wheeler and Taylor 1963, p.193).

Following this last suggestion of a hydrodynamic analogy, it is not so difficult to imagine space as some sort of ocean composed everywhere of a 'fluid substance'. Suppose in this universe, observers were constituted such that they could observe only relatively large scale motion, and were particularly attuned to perceiving angular momentum. In this case, observers would notice 'objects' like whirlpools, small eddies and the occasional swelling and subsiding of object-waves. As they could not perceive the calm 'liquid' they inhabited and which composed all the 'objects' they could observe, they might find their objects rather strange—prone to rising out of nothing and vanishing away again. Objects of a certain 'spin'—say, left-moving waves—would be tracked as moving a specific way and perhaps annihilating with objects of the opposite 'spin' (right-moving waves of the same size). If the sizes of the object-waves are unequal they would expect to find a scattering of lesser such objects produced, or simply a smaller (they might think 'more fundamental') object-wave. Extensive study might lead them to suspect that some other force was affecting many of the interactions they perceived, as if they were somehow slowed or contorted by influence from some sort of 'dark matter'. I trust the analogy is not lost on the reader, as these observers may be suspiciously similar to ourselves; the idea of spacetime relating to, and indeed forming objects in this way is plausible enough to generate the supersubstantivalist position.

Beyond such stories, why might one wish to be a supersubstantivalist? A parsimonious ontology and the models of physics seem to give a good deal of motivation. As already noted, SS makes for a tidy fundamental ontology with at least apparent room for adequately and even gracefully explaining the cosmos; spacetime regions can account for everything that we want material objects to account for and they can do it more cheaply. Additionally, physics already standardly applies a *sub*stantivalist model to its understanding of General Relativity, fields, forces and interactions (Hoefer, p.5-6) and, as Wheeler and Taylor pointed out, we certainly have not excluded the possibility of a unity of object and spacetime. There may also be further motivation from the problems faced by simple substantivalism, not least of which is the mystery of the 'occupation relation' between two distinct substances.

5.3.1 Supersubstantivalism: a closer look

Given its relatively recent emergence in the debate, supersubstantivalism has a very modest literature and could use more thorough investigation, and in this I will focus on Jonathan Schaffer's treatment of it in 'Spacetime: the one substance' (2009). In it, he argues for the merits of SS, under the terminology of monistic substantivalism (however, to maintain consistency I will refer to it as SS throughout). In particular, he advocates a version of SS that "identifies every spacetime region with a material object" (Schaffer, 2009, p.134). It is this 'identity view' of SS that he argues is superior *to substantivalism* in virtue of seven advantages: 1) its ontological parsimony, 2) the harmony between the geometrical and mereological properties of material objects and of their spacetime regions, that is, that spacetime regions are *exactly* the same shape as their material occupiers, 3) its explanatory ability to reject co-location, known as 'monopolisation', 4) its explanation for why material objects cannot exist without spacetime, 5) it explanation for the prohibition of multiply-located objects, 6) its coherence with GR and 7) its coherence with quantum field theory. Although Schaffer makes his arguments in terms of superiority to substantivalism alone, I will review some of the suggested merits in the broader discussion of spacetime theories. Ontological parsimony already having been mentioned, I will follow the remaining six as he presents them.

SS's strengths in explaining both the 'harmony' between objects and their spacetime regions (2) and the reason for monopolising the occupied spacetime region against other material objects (3) seem easily matched by rival theorists. Beginning with (2) for the argument from harmony, the relationalist dispenses with it offhand, since any talk of spacetime regions is only in virtue of objects, while the substantivalist may argue that it is only a matter of trivial definition that my hand occupies a hand-shaped region of spacetime, and thus harmony is nothing special. We only denote *that* particular region of spacetime *because* this object—with its shape—is present. Certainly we do not think there are special pre-fabricated shell-shaped regions of space that lie in wait only to be occupied by shells, and there does not seem to be any mystery in the fact that object shapes match region shapes. If any substantivalist clings to a more involved relation whereby the region seems to have the shape of its object either by unexplained coincidence or because the region causally gave the object its shape, then there may be more work for the substantivalist, though I do not think they need worry; it aligns with our intuitions and demands no special twist of natural law or any special explanation. For Schaffer, however, the supersubstantivalist is particularly well-equipped to explain such 'harmony' by responding i) that shape is typically viewed as an intrinsic property of an object—and thus the real 'object' includes the spacetime region—and ii) the allocation of geometrical and mereological properties to spacetime is an objectification that is in effect *supersubstantivalist* in approach.

However, given what Schaffer has to say about field theory (discussed shortly), it seems that he cannot put much stock in the first response, in that—as noted in Part I—shapes are not intrinsic but largely depend upon environmental factors, with contributing properties like 'pressure' *defined* in terms of the relation between an inner and outer boundary. His second response ii) may be more compelling by following Skow in saying that the supersubstantivalist may simply say that to be a spatiotemporal thing is to be a region or part of spacetime. The *sub*stantivalist is, however, obliged to say that to be a spatiotemporal thing is "either to be a region of spacetime, or to bear the occupation relation to some region of spacetime" (Skow, 2003, p.75). This further stipulation of the substantivalists makes them accept a *necessary connection* between the region occupied by parts and the region occupied by wholes (if *x* is a part of *y*, then *y* must occupy the same region that *x* does), whereas the supersubstantivalist does not have two fundamental relata to worry about making such a relation between.

However, it does not appear implausible that a substantivalist could come up with some explanation as to why certain properties are 'pinned directly' to spacetime and others are not: it may be a distinction resting with laws, or structural properties of the universe, or the nature of the properties themselves. Alternatively, there may be substantivalists that embrace a spacetime that does not exactly cohere with the shape of objects. Such a failure of mereological supervenience between spacetime and object allows for gunk and simples, which may be an asset for seeking more permissive theories.

Second, although Schaffer makes a strength of SS's dismissal of co-location (3), endorsement of monopolisation, I am not convinced that he is using a more basic relation than the substantivalist. One way of looking at the rejection is that both denials of co-location seem to assume a uniqueness of place for *substances*—different substances may intermingle for the substantivalists, but neither they nor the supersubstantivalists allow doubling up of the same substance. That is, unique spacetimes and objects can coincide, but not unique spacetime regions with other unique spacetime regions, or unique objects with other unique objects. Thus, I find that "no two distinct regions can exactly occupy one and the same region" (Schaffer, 2009, p.140) for the very same reason that no two objects can occupy the same region[52]. Regions may not have an occupation relation, but they are located in some sense (perhaps relationally), and no two unique regions can be located in the same region, i.e. no two regions can co-locate. Similarly, objects are located at regions (it is part of what being an object is); that is, the substantivalist may simply define the 'containment' or 'occupation relation' between spacetime substance and material substance to mean the principle of harmony that Schaffer alludes to and so make that relation do all the work. In that case, it is the nature of objects, spacetime, and the containment relation that objects exactly and entirely occupy spacetime regions (perhaps in much the same way that objects put underwater occupy a region of 'no-water' that is their shape).

Third, there is the argument from 'materialization' (4) that appeals to the intuition that an object cannot exist outside of spacetime, allowing SS to give an easy explanation for why it cannot. While it may be too much to speculate here on the physical need for spacetime for the existence of objects, the claim does reveal important expectations and uses for spacetime in our conceptual processes. It is not mysterious to the substantivalist that her *contained* items (objects) should always be found in a *container* (spacetime), indeed, they may not find it a difficulty at all, but a primitive relation or entirely 'natural' (see Hudson p.4). This is a strong intuition but it does take more primitives and an additional location relation than supersubstantivalism needs, and that is arguably an additional reason for accepting the latter position.

[52] Alternatively, co-location may be equally possible for either theory in terms of multidimensional regions and objects.

Fourth, Schaffer sees SS as rejecting the possibility of multiply-located objects (5). However, it is not yet empirically obvious that the possibility of multiple-location is a problem, and it may be even useful in addressing phenomena like entanglement (see chapter 8). Indeed, some may view it as a weakness of his SS that it ostensibly silences this possibility of multiply located objects. There may be ways out for the supersubstantivalist though, in allowing the definition of an 'object' to range over geographically disparate but in some sense unified properties in much the same way that the substantivalist can contemplate such objects. Philosophers (Hudson 2006, Parsons 2006) have taken great interest in discussing such exotic objects in a substantival context, which the supersubstantivlist is just as able to use.

The philosophical justification that Schaffer invokes is similar to what he used for rejecting co-location: "material objects *are* spacetime regions, and no one region can be two different regions" (Schaffer, 2009, p.142). He takes this as a much more obvious claim, it appears, than one involving the occupation relation, which the substantivalist might as easily define as being exclusive; for instance, the substantivalist might say that 'to be a material object is to be contained in one spacetime region, and no one spacetime region can be two other regions'. That is, substantivalists can give a different and more exclusive definition of the occupation relation (perhaps in terms of a containment relation) than Schaffer gives them credit, or they might again focus on the exclusivity of the *same* substance while allowing the mixing of different substances.

The last two defences Schaffer rallies to the cause are standard interpretations of the very successful theories of general relativity (6) and quantum fields (7). The absence of material bodies as we typically think of them in such theories (ranging over both the very large and very small) gives a compelling endorsement of SS. Such an approach is not without its problems however. There is the concern—for SS as much as for substantivalism—that we take mathematical models of reality too literally or simply end up with no way to translate the one into the other. On the other hand, a large explanatory gap remains between analysis of relativity and the quantum world that may reverse the primacy of substances such that spacetime is an emergent property of some deeper *material* order (Seiberg 2006). On balance, however, and giving cautions where they are due, SS possesses much to commend it by embracing the science and streamlining the philosophy of the relationship between objects and spacetime. Indeed, despite finding Schaffer's arguments somewhat modest, I think the strengths of parsimony and agreement with physical theories remain compelling and sit well in a world picture where particles appear and disappear amid an energy sea.

But if it is such an able means of tying up our loose threads, what reasons do we have for *not* adopting SS? The common responses generally rest on intuitions and the unnatural phrasing, which is noted so vividly by Ted Sider: a region of spacetime bounded out the door and barked at the mailman'—it sure sounds strange to say! Indeed, it sounds like a 'category mistake'. But this is not a good reason to resist the identification, any more than the strangeness of saying that pain is located in the brain is a good reason to reject the identity theory of mental states" (Sider, p.110-111). Nonetheless, we might object that, beyond our expectation of traditional objects, spacetime points or regions are a) not the sort of things that *move*, or, as with substantivalism, b) not the sort of things that could be anywhere other than exactly where they are—that is, the *de re* modal properties of SS are different and more restricted than those of substantivalism.

To these concerns I add c) the conceptual discomfort over using points to ground concrete properties. Given our experience of object motion and an indeterminate universe, the first two should be concerns for SS. Taking a) first, Skow, for instance, suggests that "it seems necessary that the distance between any two points of space be the same at all times" (Skow, 2003, p.81)[53]. In order to maintain both the observation of motion and the notion that points in space do not change position over time, Skow suggests one might either deny what he calls mereological essentialism (whereby points stay the same but the regions encompassing them can change), or deny that particles really move. Although he finds both views distasteful and rejects them in favour of a four-dimensional spacetime, I want to linger on whether both are so obviously unsatisfying.

The first option does not appear much removed from our everyday conceptions of identity, whereby we have, say, a persisting region of 'mother' despite that region being composed of different constituents at different times (cells, atoms etc.). Under this rejection of mereological essentialism, the supersubstantivalist might understand material objects as an arrangement of property instantiations that held in certain relations even as the particular points manifesting those properties changed. The second option also seems a relatively easy concept to entertain, particularly as the illusion of movement is something we regularly

[53] This assumption may also be a problem for substantival models of universal expansion where presumably points either move or have new space appear between them.

encounter. Indeed, it is quite palatable to conceive of spacetime points instantiating properties in a sequence to produce the ‘motion of particles’ in a way that is similar to the ‘motion’ observed on computer screens.

The minute array of pixels (spacetime minima) may light up in such a sequence that we perceive a single unified object in motion, but that is not what actually happens. One need not accept a 2-dimensional universe to consider such an illusion, and further, it is an option for the supersubstantivalist toolkit. This account of motion may also be able to model problematic quantum phenomena in a new light; that is, SS may be able to explain the phenomenon not by looking at the permeability of spacetime but by allowing non-adjacent spacetime regions to instantiate the set of properties that denotes a ‘material object’. Under this view, we need not explain why the object appears to move faster than light (there is no object in that sense), rather we would need to explain why there was a non-adjacent instantiation of the property set that constitutes the object.

Objection b) contrasts the intuitions that spacetime points are necessarily positioned as they are and that material objects have the possibility of being located elsewhere. This is seen to pose a challenge to SS since objects and spacetime points are equated, but the supersubstantivalist can offer several replies. First, she may say, as Skow suggests, that such modal talk about objects is context dependent, and that the two claims are never both true in the same context so that we might find geometric duplicates of spatial regions without finding material duplicates exactly overlapping. That is, one might specify that in

> contexts in which we are thinking about regions of spacetime as regions of spacetime…we use a counterpart relation that values geometrical similarity [while] in other contexts…in which we are thinking about regions of spacetime as material objects…we use a counterpart relation that values other kinds of similarity—like similarity with regard to mass and charge distribution—over geometrical similarity (Skow, 2005, p.84-5).

Second, the supersubstantivalist may reply, assuming she does not want to commit herself to a deterministic universe, that spacetime points are *not* necessarily positioned as they are and thus dispense with the further concerns of context; spacetime points, then, do not have their geometrical properties essentially.

Third, she may argue that there is no contradiction and that SS may accept both that spacetime points could *not* have been otherwise located while material objects *could* have been otherwise located because there is nothing in the proper interpretations of object, motion or location that prevent this from being the case. This third option amounts to the claim that even if spacetime points could not be otherwise positioned, the properties they instantiate could vary over possible worlds. Any viable SS theory will have to allow for spacetime points to alter their instantiated properties over time anyway, and this allowance coupled with our description of illusory motion does not require spacetime regions to move, but only some set (whatever it might be) of relations or properties to hold. As for c), the grounding of all concrete 'matter' in points, I think the supersubstantivalist can embrace a region-based approach instead, though I do not know that this is more beneficial than pursuing dense relationalism. I take up my concerns with points in chapter 7, so I will here merely note the conceptual disconnect between points as we mathematically understand them and the perceived properties instantiated in the world. This connection could use more elaboration and explanation to make it accessible, for points-based SS as much as for substantivalism.

In summary, I think the three approaches examined—relationalism, substantivalism and SS—all have merits and weaknesses such that they should be eligible for physical testing. However, I think there are particular problems for substantivalism—beyond the explanatory deficiencies arrayed by Schaffer and Skow—that will occupy the bulk of the next two chapters. I cannot discount the possibility of substantivalism at some point developing better responses to questions about the occupation relation or the fundamental difference between spatial and material stuff, but as it stands and as I will argue, it is under significant pressure such that we should look to monistic ontologies. That is, I think there are good reasons to more thoroughly examine a *singular* ontology theory, whether supersubstantival, relationalist or another new one. Given the concerns about isolating objects and intrinsic properties of Part I, SS and dense relationalism are particularly philosophically appealing for their a) parsimony and b) relaxation of the classical object/space distinction, and c) the *mathematical* retention of a points-based system. That is not to say that we cannot formulate a rigid set of criteria that still distinguishes *this* thing here as an object, but it does relax the quest for ontic separation since, technically, everything—whether classed as an event, object or space—is made of the same fundamental stuff. Such singular ontological models offer a compelling substitute to bear in mind when reviewing some of the challenges traditional substantival theories face in light of physical phenomena in the next chapter.

CHAPTER 6: Physical Phenomena

The previous chapter gave a critical overview of the main philosophical theories of the relationship between objects and space, with an extended look at supersubstantivalism (SS). Fairly oblique references were made to the intersections with physics, so I will here explore a selection of the more challenging phenomena (as in Part I) to substantival explanation. Again, I will use 'space' and 'spacetime' interchangeably unless there is a relevant distinction to be made or unless otherwise specified. Space is often measured by objects, but it is not clear if the objects are *in* space or are a *part* of it; it is not obvious we have good reasons to think one way rather than the other, and there are problems with standard dualistic frameworks of the former case.

First, I will look briefly at objects through space, generally interpreted as fields, which are often claimed by both relationalists and substantivalists as material or spatial stuff, respectively. Second, I will explore 'empty' space, arguing that its fundamental energy values make it a stronger candidate for material substance rather than a unique spatial substance (as substantivalism claims). Third, I will argue that spatial expansion is similarly an issue for traditional substantivalists who owe us an explanation. Finally, I follow a similar concern looking at the possible *emergence* of space from dynamic quantum networks, thus removing space from our fundamental ontology. I conclude that there are significant reasons to pursue other singular ontological models than substantivalism.

6.1 Objects *through* Space: Fields

One way a substantivalist understands an object's relation to space is to invoke fields, though their ontological status is uncertain, applicable to either objects or spacetime; indeed there is a tradition from at least Michael Faraday onwards that has attempted to explain physics in terms of a *unified field* theory, which a single ontology may be particularly able to address; given the interplay between matter and energy (discussed below), it is insufficiently motivated to assume space is a separate substance, and thus, that substantivalism is warranted. Part of the impetus for embracing a basic ontology of fields can be traced through discussions of object borders and what constitutes 'contact'. The majority of such discussions assumed space and time to be continuous, and so wondered whether the volumeless point of contact between two objects, spheres, say, could belong to both, to one or to neither object.

While no answer was particularly satisfying, fields offered a way of understanding forces and interactions that allowed two objects to come into 'contact' through their respective fields with a boundary that neither one possessed. Indeed, phenomena like electromagnetic repulsion can be understood entirely through fields, either by *surrounding* matter, or matter being entirely *composed by* fields of repulsive force (Lange, p.169). Thus the location of a particle is just the centre of a field, which is thus in principle capable of passing through or coinciding with other fields in the same point. The energy of a particle will be a multiple of the field's frequency (Nimtz and Haibel, p.82), and it is such differences in energy potentials between particles and their surroundings that in turn determine the field, leading to a curious and sometimes unclear interdependency, suggestive of an underlying connection and posing a challenge to substance dualism.

Fields have been critical in accounting for the behaviour of many particles and forces such as electromagnetism, and the distinction between such fields and space is particularly unclear concerning gravitational fields that are thought to warp and contour space itself. Gravity is thought to be exchanged through massless gravitons, however, and thus adheres to a particle ontology as well as constituting space. This blurring between object and space occurs at the minute level as well; "in quantum field theory, the distinction between particles and fields seems to disappear, or at least to become much more difficult to draw" (Lange, p.171). This merging of disparate metaphysical entities is disconcerting, and perhaps even alarming when one notes a long-standing disagreement in the scientific community about whether fields are in fact *real*. Marc Lange's thorough investigation of this debate reveals marked confusion between and within textbooks that take sides on the issue or even call fields a reality or a fiction from one page to another. Nobel laureate Percy Bridgman argued that electric fields were a fiction never subject to direct observation (Lange, p.41) while many modern theorists claim that fields are "a physical quantity that *exists* and has a particular value for each point in space" (Randall, p.462, emphasis added).

So what is the ontological status of fields and how are we to understand the relationship between objects and space in terms of fields? The answer is an issue of ongoing debate, though, again, our uncertainty as well as explanatory simplicity give us cause to explore non-substantival options, especially as our understanding of fields has wider metaphysical implications. For instance, if fields are real, then electromagnetic interactions between bodies are spatiotemporally local; if they are not real, then there appears to be non-instantaneous action at a distance (proceeding at the speed of light). And given relativistic concerns prohibiting a preferred reference frame, then merely electric or magnetic fields are want to disappear depending on the observer—making only their unification in an electromagnetic field, which can be referenced regardless of the observer's position, an appropriate candidate for a real entity. While the debate concerning the reality of fields is interesting in itself, I will assume that they are real in some sense, and thus that gravity and electromagnetism are local forces. Under this assumption, one can compare the different properties attributed to fields, objects and space to better understand how the latter two interact.

Perhaps the most curious property of fields is their scope, as was referenced in Part I. They are perceived as extending out to infinity with properties such as *mass* or *charge* 'centred' in some region. They are also able to thus extend and have non-zero values whether or not there is any body—any recognizable 'object'—there to experience it. These aspects certainly seem to partake of both spatial and material properties, and, I think, challenge substantivalism's traditional dualism. For instance, while a body can cause electric force only around other charged bodies, the electric *field* can have a non-zero magnitude even in 'empty' space. Such quantum fields are thought to be "eternal, omnipresent objects that can create and destroy…particles…[and] permeate spacetime…For example, an electron or photon can appear or disappear anywhere in space…Each particle is created or destroyed by its own particular field" (Randall, p.158). This may be an unintentional designation of a field as an object but it is not an uncommon view. The 'vacuum' state of space is then filled with (or composed of) fields that may change at any point into a state that can "contain fields with bumps and wiggles corresponding to the particles" (Randall, p.158).

If the basic constituents of matter (objects) are created and destroyed within their particular field (e.g. photons in electromagnetic fields), then one may wonder whether fields are really the fundamentals of matter or whether fields simply *are* space, or perhaps, as I have suggested, some combination of the two. Although more physics would go a long way in determining the confusion over field ontology, I think this interchange between what are typically seen as material objects (particles) and the form of space (fields) is suggestive of a unified singular ontology of substance. Indeed, given the interchange of energy and mass, which characterise, respectively, spacetime fields and most objects, we should be immediately struck by the underlying unity and find any theory of dual substances concerning. If there are any fields identified with 'space', rather than fields *in* space, and they are found to produce particles, then a dual theory of substances is very much in trouble.

Both points-based and regions substantivalism are so appealing because of their fit with science, but if space is interchangeable with matter, then the model can hardly be worthwhile. Relationalism, dense relationalism and SS all appear better fits to the above field models, but perhaps a closer approximation to *spatial* fields can be found in 'empty space'.

6.2 Empty Space?

Another key point of interface between matter and space for the substantivalist should be visible in 'empty' space, where an absence of matter could better reveal spatial nature. Although we have a verbal distinction between space and 'empty space', there is a tendency in common parlance—and to an extent in some scientific discourse—to think of space as an empty container for matter. We might inscribe a metric in or over it, and space may be seen to rather mysteriously curve and respond to matter, but we traditionally do not expect it to change type, that is, to allow the 'something' of material objects to come from the 'nothing' of empty space. However, something very much like that appears to occur, and clarity of definition will be particularly important here. Bede Rundle notes this concern so that,

> may or may not say that a space is empty if there is light or gravitational waves passing through it, and we have to devise criteria for saying that a field permeates space. These are conceptual issues, but I do not think that logic extends to ruling out the very possibility of (an) empty space. Rather, having decided what is to count as something in space, it is then an empirical issue whether a space is empty or not. What is hard to fathom is the claim that space is totally empty and yet that that emptiness coexists with such properties as that of curvature, which is referred to space itself and not to something within space (Rundle, p.215).

Rundle's concern with space possessing matter-like properties (such as curvature) is often dealt with through the mediating influence of fields, which provide an accepted means of characterising certain properties throughout some sort of extent, presumably a spatial extent. 'Field' is a slippery concept, itself worthy of extensive analysis, but it might roughly be thought of as "some aspect of the properties of a region of space that can be quantitatively assessed at every point in that region" (Schumm, p.51). While useful practically, this sort of working definition reveals little about the theoretical underpinnings of a field or how best to interpret it. Nonetheless, if we keep with such a working definition we can define empty space in terms of either an absence of fields or a zero-value for all fields. Physicist Brian

Greene assumes that this latter option is the more intuitive, but argues that such a notion of emptiness “is incompatible with quantum mechanics. *A field’s value can jitter around the value zero but it can’t be uniformly zero throughout a region for more than brief moment*” (Greene, p.330-1). Indeed, physicists conclude that “emptiness is unstable” (Wilczek and Devine, p.244).

Furthermore, if we take the standard interpretation of fields to be an instantiation or property of space, then “such quantum jitters mean that the shape of space fluctuates randomly” (Greene, p.333). This kinetic view of space is what keeps it from being empty; the movement of the field values and that change in potential energy reflect a structured ‘something’ that suggests *space* is not *empty,* at least not empty of matter-forming energy; indeed, ironically, “the vacuum is generally regarded as full…with an immense energy of fluctuation” (Bohm and Hiley, p.38). This view is shared on a basic philosophical level where space is certainly not totally empty—it is full of itself, of spatial substance (e.g. points). But if we mean it to be a substance that tolerates points and the abstractness of mathematics, it is unclear how it could ever interact with the concrete world we perceive.

Whether abstract or no, an empty space does not equate with philosophical nothingness. Indeed, for the theory of general relativity, “space itself can assume properties, and, as a consequence, ‘empty space’ does not automatically qualify as ‘nothing’. Theories that include quantum mechanics don’t admit any empty space at all, simply because the uncertainty relation and the special theory of relativity force onto it vacuum fluctuations that will fill space” (Genz, p.307). Part of this energy seems trapped in the structure of ‘space’ itself, which is often assumed to encompass the Higgs field and its mass-giving properties. Such a structure gives a negative energy to space that cancels the positive energy of the field’s own existence (Genz, p.230).

So while this relation gives a good reason for why our universe is a structured one (by being the lowest equilibrium state), it also preserves “a remaining ‘ground state energy’ even at absolute zero temperature, which cannot be removed from any volume” (Genz, p.181). Indeed, ‘nothing’ in this sense, is unstable, with quantum fluctuations and the negative pressure of space countering gravity and implying ‘that, under the right conditions, not only can nothing become something, it is required to” (Krauss, p.156). That the matter and fields with which we are familiar are thought to issue from the ‘nothing’ of space, and indeed that, given initial conditions, there is a certain inevitability about it, indicates a fundamental connection and shared constitution between space and objects—a monistic substance of 'spacematter' that need not make one or the other traditional substances more primitive.

If we allow empty space to be inhabited, and even determined, by quantum material fluctuations—which seem to give rise to material particles—then we have reason to question the space/matter distinction. Contrarily, if we interpret 'empty' to mean devoid of quantum material fluctuations (including virtual particles and energy values), and if the laws of physics prohibit a completely empty space, then we have reason to dismiss space as a substance and embrace a dense relationalism or supersubstantivalism in our world. Indeed, it is often assumed that what we refer to as a fundamental particle is only the ordered excitation of fluctuating space, or a type of quantum fluctuation (Genz, p.215). These excitations could take the form of strings or fields with compact centres as our best theories suggest, portraying interactions as the collision of certain types of fluctuations with other types. In either case, this sort of conception is sympathetic to the interchangeability of 'space' and 'matter' and it is along these lines that a form of dense relationalism or supersubstantivalism looks particularly appealing. 'Empty space', then, may pose a problem of definition, but it also suggests a much more intimate relation between objects and space through the convertibility of both to energy. This integrated account can easily coincide with a monistic substantivalist approach and the expansion of interdependent properties referenced in Part I. Again, the interchangability of matter and space makes substance dualism seem a hyperbole that should be left in favour of other models.

6.3 The Creation of Space: Expansion

Part of the traditional substantival picture portrays spatial points as stationary and as a firm background on which to 'pin' mercurial objects and phenomena, and so we might wonder if under this view space is something that can be created or 'moved'. The expansion of the universe and the suggestion that spacetime might be an emergent feature of certain quantum processes both seem to press the issue and require some sort of philosophical explanation. While the scientific community readily agrees that the universe is expanding, there does not appear to be a rigorous theory about what this means for space. We do not know whether this means that spatial fabric is stretching, new spatial material is forming, or simply if the distance between visible matter on our cosmic horizon is increasing. We lack so much in the way of details about space that there does not seem to be any exclusively obvious philosophical or physical interpretation. Our best physics states that observations indicate a substantive ‘dragging’ of energy waves that is generally interpreted as space expanding, though again this need not be the case.

For instance, physicist Steven Weinberg states as an aside, and without much in the way of explanation, that “it is misleading to say that the universe is expanding, because…space itself is not expanding” (Weinberg, p.34). It is unclear what he takes spatial ‘expansion’ to mean, particularly as he doesn’t offer an alternative interpretation. Although vague, we get a slightly more revealing suggestion from physicist Leonard Susskind who thinks “space itself is reproducing to fill the gaps. One might say that space is cloning itself – each small volume giving birth to offspring, thereby growing exponentially” (Susskind, p.299). Such a cloning process is entirely mysterious and neither physicist gives a clear expression of spatial expansion in these terms or otherwise, though this account may find greater purchase in combination with an emergent view of spacetime that takes quantum fluctuations as more basic. Whatever specific explanation is given, an understanding of the relational and theoretic underpinnings would be advantageous. Presumably, philosophy is well placed to analyse the implications of various models, chief of which may be its own favoured options, substantivalism included.

There are a few key physical reasons to think space is expanding, all of which rely on the beliefs that 1) the volume of space is in some way importantly confined to our universe, 2) our universe is expanding, and 3) we can know this by the growing distances between galaxies coupled with our central cosmological theories (especially the big bang theory). Notably, these beliefs are heavy in the way of philosophical assumptions; denying 1) or 2) will do away with the issue of spatial expansion altogether, but since we only have empirical access to 3), this is where we will start. There are many astronomical sources that could be used, but I will take advantage of Giovanni Macchia’s paper on the subject, given his background in astronomy *and* philosophy. In (Macchia 2010) he argues that cosmological expansion gives us reason to favour a substantivalist perspective over a relationalist one. He follows J. R. Peebles in defining such expansion as indicating that “‘the proper physical distance between a [typical] pair of well-separated galaxies is increasing with time, that is, the galaxies are receding from each other’ (Peebles 1993, p. 71) with velocities proportional to their distances” (Macchia, p.104).

Describing universal expansion as merely an ‘increase in distance’ may be motivated by our inability to define absolute velocity across a large non-Euclidean universe, but it sidesteps all the ontologically significant particulars. Through a compelling analysis of the mathematical expressions, Macchia interprets this stretching of photonic wavelengths as "a relation between emitter and observer operating just through space, not across it: light is redshifted just because it 'clears a path' through an expanding metric that, point by point, influences its wavelength" (Macchia, p.127). He further aligns redshifts, along with the absence of kinematic terms in its cosmological formulation, with "a universe consisting of expanding space (in which a continual expansion of space is 'pulling along' galaxies fixed to it)" (Macchia, p.108). Our conception of the expansion of space is most notably derived from the 'recession velocity' of observed galaxies, which Macchia argues is not merely local movement of objects within a container spacetime, but rather the global rate of increase of the metric itself (i.e. the basic units of measurement are themselves growing *between* but not within galaxies). The movement of light is a privileged observational tool here, as in many other instances, because noncoherent objects like photons have wavelengths that are affected by cosmological evolution in a way that galaxy-bound objects are not.[54]

The received understanding that Macchia explores[55] takes the empirical data from galactic optics to mean that there is a "global recession of galaxies [which] originates in the dynamical evolution of the universal spacetime metric, and not from the effective motion of galaxies *through* a *static* space" (Macchia, p.104). Thus, he argues that observation reveals an *evolving* fundamental metric (spacetime), and this evolution is in turn interpreted to mean the fundamental metric is *expanding*. Macchia concludes with a final endorsement of substantivalism, interpreting redshifts as demanding something physical to propagate the wave energy "between the times of physical phenomena of emission and reception… Therefore, both in the cosmological redshift and in the gravitational wave cases, a substantival metric field, i.e., a structure that can carry and store energy, is needed for the explanation of these cosmological phenomena" (Macchia, p.128-9). But this *physical* structure that can carry and store energy seems, as defined, to be commensurate with the description of a *material* field. Indeed, it is not obvious that spacetime substance should have claim on such a field rather than material substance, despite Macchia's claim that the metric field "can exist without any material content, but the opposite is not true" (Macchia, p.131).

[54] It is thought that at scales the size of galaxies and smaller, the cosmological expansion does not hold because all the other forces (as well as the local gravitational fields) are so much stronger than those between widely-separated galaxies. In a steadily expanding universe, the compromise between local forces reaches equilibrium to maintain a certain size (that nonetheless would have been smaller or larger if global gravity were different). It is only in a universe of accelerating acceleration that we should be concerned about a great 'rip'.
[55] See, for instance (Davis and Lineweaver 2004).

Substantivalist theories are appealing, here, because they preserve the explanatorily valuable idea of expanding spacetime, which itself gives a useful framework for explaining many of the interactions and properties of fields and objects. Rejecting the idea that the energetic, field-rich vacuum is of the material substance, Macchia thinks the relationalist has to give a less satisfying account, which "would be sustainable only in arguing in favour of effective galactic motions through a non-expanding space; in particular, relation[al]ists would have to resort to Doppler interpretations and accordingly fall back on cosmologically unfruitful descriptions based on Special Relativity" (Macchia, p.105). While it is true that resorting only to Doppler effects would limit relationalism's viability, it is still possible that a reinterpretation of the data along other lines (perhaps taking 'dense relationalism' more seriously or perhaps when the effects of the hypothesised dark matter are better understood) may leave the relationalist's position tenable and even give her an advantage since she does not need to explain what 'spatial expansion' means, though prima facie her tool kit seems no better suited than the substantivalist's; the possibility of spatial expansion is more a hurdle than a falsification of relationalsim.

While generally sticking to the safer structural talk of spatial expansion in terms of increasing distance, Macchia admits a brief moment of reflection and tantalisingly asks what it really means; "is it an actual incessant creation of space, that is a kind of production of a larger spatiotemporal container added with vacuum? Is it a sort of stretching of an infinitely elastic substance that 'extends' its points?" (Macchia, p.118). Unfortunately, he only raises such questions to show them the door, following Misner in dismissing that sort of thinking altogether: "to speak of the 'creation' of space is a bad way of speaking….The right way of speaking is to speak of a dynamic geometry" (Misner et al. 1973, p. 740). Despite criticisms that such questions are the wrong ones to ask, it isn't clear that one is maintaining a cohesive substantivalist ontology if the trickier areas must resort to a different explanatory paradigm (e.g. dynamic geometry).

That is, if we are to take spacetime points (or regions) as real and if we take the expansion of spacetime as real, it is a perfectly reasonable question to ask what these two assumptions imply; are the distances between spacetime points/ regions expanding, and if they are is that new 'distance' spacetime as well? Or are there more points coming into existence to account for the increasing volume of the universe? Substantivalists (and supersubstantivalists) should take these questions seriously and offer an account of whether space is something that can be created or modified in this way. As mentioned earlier, one approach is to deny the assumptions that lead to us thinking that space is expanding, and so reject that ‘retreating’ galaxies imply anything about space, or that what we call the universe is a boundary to space, or yet some other divergence. But if the substantivalist proceeds down these paths, we will need a more sophisticated understanding of the galactic redshifts and what other aspects can account for observed phenomena. Here, then, the substantivalist owes us an explanation despite its prima facie advantage of offering a medium (space) by which to drag galaxies. If it cannot given an explanation, then more work is needed on fleshing out the content and structure of the theory, and we have reason to look elsewhere for explanatory models.

6.4 Spatial Emergence

Another reason we are lead to address the creation of space comes from the suggestion that space (and spacetime) might be an emergent phenomenon, created through certain minute interactions such that it *depends* for its existence on matter, and is thus arguably not a distinct substance at all. This view is, of course, quite opposed to both substantivalism *and* SS, and perhaps most closely aligns with relationalism and dense relationalism: matter is fundamental, ubiquitous and space depends upon it. For several decades there has been a suspicion that space and time may be our macroscopic approximations of a very different looking theory[56].

The creation of space in this way would take on a different meaning than the ‘property pin cushion’ of substantivalism, since space would be re-imagined as a fluctuating entity that could at most be ‘pinned’ with less fundamental material properties and larger objects. And in this, it could lose any sort of fundamental metaphysical role even if physical significance remained. Here, as with other theories, it is the viability of the model rather than the proof that commends our attention, and it is something that physicists like Lisa Randall take seriously. She suggests that “one of the most important lessons of the perplexing discoveries of the last decade is likely to be that space and time have more fundamental descriptions…David Gross imagines that ‘Very likely, space and perhaps even time have constituents; space and time could turn out to be emergent properties of a very different-looking theory’” (Randall, p.454, with quotes from K.C. Cole’s article ‘Time, space obsolete in new view of universe’ *Los Angeles Times*, November 16, 1999).

[56] This suspicion is somewhat brought to light by Barbour in *The End of Time*, 2001.

Nathan Seiberg also endorses such a view, suggesting that space and time "will not be present in the fundamental formulation of the theory and will appear as approximate semiclassical notions in the macroscopic world" (Seiberg, p.1). Indeed, theories from twistors[57] to strings are considering the possibility that spacetime is emergent, that it is not a fundamental component of our world but a phenomenon that appears at a higher level. In examining the implications of string theory, Greene argues that in "the raw state before the strings that makeup the cosmic fabric engage in the orderly, coherent, vibrational dance we are discussing, *there is no realization of space or time*…. In a sense, it's as if individual strings are 'shards' of space and time, and only when they appropriately undergo sympathetic vibrations do the conventional notions of space and time emerge" (Greene, 1999, p.378). Questions of emergence arise not only from string theory, but also from the lack of spatiotemporal variables in fundamental formulae used in attempts to combine relativity theory with quantum theory and even in the more radical approaches to higher dimensional algebra, where "the concepts of 'space' and 'state' are completely merged in the notion of 'spin network', and similarly the concepts of 'spacetime' and 'process' are merged in the notion of 'spin foam', eliminating the scaffolding of a spacetime manifold entirely" (Baez, p.194). Admittedly, this is only so much speculation, but there are problems that such a move might solve and reasons for taking it seriously.

For instance, Olaf Dreyer argues that the difficulties posed by the cosmological constant and time in modern physics can be eliminated if, rather than treating spacetime as a separate object from matter, space and time are treated as emergent concepts. That is, a spacetime appears only through the excitations of the quantum fields (Dreyer, p.11-12). Dreyer's account relies upon, what he calls 'coherent degrees of freedom', which controversially "play the role of matter… [and] are also used to define notions of space and time. It is because they play this dual role that the equivalence principle and also the Einstein equations are true" (Dreyer, p.13). Dreyer may be seen to uphold a relationalist or even a supersubstantivalist perspective by rejecting any notion of spacetime without matter and instead favouring the parsimonious unification of spacetime and matter in the actualisations of degrees of freedom. Again, there is little positive theory to interpret here, but the direction of the speculation is not without a long-standing engagement with the ideas, including the 'halfway-house' of a holographic model.

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[57] "On a sufficiently small scale the concept of a space-time point evaporates…Instead you have the intersections of twistors that model light rays" (Gardner, p.253).

Taking its cue from the astrophysical formulae describing a black hole's mass, holographic theory supposes that if the maximum information (and thus entropy) in "any given region of space is proportional to the region's surface area and not its volume, then perhaps the true, fundamental degrees of freedom – the attributes that have the potential to give rise to that disorder – *actually reside on the region's surface and not within its volume*…Maybe, that is, the universe is rather like a hologram" (Greene, p.481). The first part of this argument is less controversial than the conclusion, as there is a common belief that there is a limit to the amount of information and energy that can be contained in a region of space, our understanding of black holes says as much.

This lurking suspicion of spacetime has been on the go for awhile and has many contributors, but it is quite a leap to suppose from this suspicion and the surface density of black holes that information is thus "stored on surfaces, or screens. Screens separate points, and in this way are the natural place to store information about particles that move from one side to the other" (Verlinde, p.6). It is hypothesised that particles approaching these screens influence (perhaps true 'spooky action at a distance') the information stored there even before they combine with it. The screens also determine a special direction to space in much the same way that time is directed. Thus, there is one direction "in which space is emergent…the screens that store the information are stretched like horizons. On one side there is space, on the other side nothing yet" (Verlinde, p.6).[58] The possibility that there is a direction to space is intriguing, if underdeveloped, though that in itself need not be a problem for substantival theories (though of course a dependent emergence would be).

Whether holographic in this way or not, spatial emergence may prompt substantivalists to disassociate such 'emergent space' from their philosophical conception of the philosophical underpinning of matter and thus chalk up the mismatch to linguistic faults (e.g. *that* sort of space is not what we really mean in the metaphysically grounding sense). This sort of response looks to the practically relevant rather than the theoretical principle, however, and would need to be acknowledged as an approximation, which is not unlike one of the options discussed in terms of intrinsic properties; colloquially we might still point to mass and shape as intrinsic, but for academic accuracy we can no longer be so sloppy. Similarly, substantivalists might also argue that such space is so minute that it can still act as

[58] One might stave off this problem, however, by interpreting the screens as just one large dimensional boundary to a higher dimensional universe, and because we (along with all the forces but gravity) are confined to this boundary/ screen, we only see the 'shadows' of interactions in the larger 'bulk' universe.

a grounding for all the sorts of properties *we* talk about. This might lead them to shift to an 'almost fundamental' ontology whereby space depends on material substance at a fundamental level, but above that there is utility in separating the two substances. Supersubstantivalists will face the same options, which would make some other theory of monistic ontology with a single master substance that accounts for space and matter more appealing.

In summary, there are areas of physics that are at odds with the notion of dual fundamental substances—an important element of traditional substantivalism in both its points-based and regions-based formulations. The interchangeability of fields and 'empty' space to comply with both material and spatial needs indicates an underlying unity that makes dualistic theories unwarranted, while expansion presents substantivalists with challenges that need addressing in any case. Emergence is only a possibility at this point, but it is a suggestion that opponents of substantivalism will find encouraging, and certainly if it is proven accurate then there will be no keeping up appearances for the theory. As it stands, the weight of ontological commitment that attends embracing substance dualism is too heavy given the ontological unity of physical phenomena and so I advocate departing from current substantivalism to develop singular ontological models.

CHAPTER 7: Location and Points

Beyond physical rationale, I think there are philosophical reasons for finding substantivalism troubling, namely in the way space (and spacetime) *locates* objects, since the material substance somehow 'occupies' the spatial substance. That is, I take issue with substantivalism's interaction between two distinct substances; while some auxiliary good may come from considering new object types, but such consideration is dependent on subtantivalism and the interaction with space remains mysterious. For the substantivalist, space is generally perceived as something of an unprejudiced landlord that allows all manner of occupation by all manner of objects: a horse may be located in region *r* at time *t*, while a car may be located at the same region *r* at time t_1. Further, the horse or car may be located in a variety of ways, from only partly to wholly to exactly located. Despite the fundamental difficulty in conceiving how two distinct substances interact, there are benefits to exploring new models for objecthood that attend this area of enquiry, particularly as concerns the science of the last century. Reconceptualising objects in this way sustains the theme from Part I as well as raising concerns for reconceptualising space and pursuing singular ontological models.

Although limited by empirical demands, we can hope to get a better idea of some of the benefits of and challenges to substantivalism in regards to the occupation relation. First, I will explore the ways an object might be located at or occupy spacetime in substantival models, examining the strengths and weaknesses of this approach, including the difficulty of making sense of substance dualism. Second, I will look at a case study created by Josh Parsons that pulls these elements together and gives an idea of the metaphysical intersection with modern physics. Finally, I look at the substantivalist's use of points and the conceptual challenges that attend them, particularly as something interacting with material substance.

7.1 Location

Theories of location rely on a particular blending of a theory of spacetime structure, and a theory of what sorts of things count as an object. The majority of discussions on location assume—following traditional physics—a substantivalist framework[59]. This substantivalist bias may seem appropriate for the idea of location—and has its benefits—but it is not without

[59] Location for relationalism involves relevant relations to other bodies while SS can either rely on relations to other points/ regions or to the individuality of them (e.g. point 132).

its problems and, as with most locational theories, is underdetermined by the data. Moreover, the benefits it provides can be achieved in other ways; i.e. by exploring different models for objecthood without assuming that they need to interact with a separate underpinning substance. I see the benefits of such exploration to reside in the receptivity to new models for the configuration of objects; not only can these models be adopted by any of the object-spacetime theories discussed in chapter 5, but they have the potential to better fit with discoveries in physics than classical object models do. One might also claim that such explorations are beneficial because they offer a way to maintain locality and familiar causal stories that seem unavoidable in physical experiment. I think there is thus some merit in this and am happy enough to compare the terminological uses and general differences among location relations in hopes that the above elements do prove fruitful.

However, in regards to the particularly substantival aspect of 'occupation', I find these explorations perplexing, particularly because it is meant to somehow importantly bring two *distinct substances* together and have them interact (e.g. if not simply through the 'occupation relation' itself, then through spatial warping in response to matter). The occupation relation is a weakness in the same way that the Cartesian pineal gland was: it is mysterious. I admit that I have no idea what talk of occupation relations mean, as it seems suspiciously caught up in our everyday experience of material objects. If spatial points are real, how exactly are such points occupied? Could the point ever lose its property of 'containing'? Do objects really need space to exist, and if so, does that not mean that they are not of an independent substance, and thus that we should pursue relationalist or supersubstantivalist approaches? I do not even have an idea how I would answer these questions, and expect a much clearer account from the substantivalist on this score. If she is as baffled as I am, then I think there is good cause to step back from the model and explore others. Despite my strong misgivings in this respect, I think the previously mentioned benefits merit a review of the ways an object might be located.

7.1.1 Ways to be located

Most discussions of location adopt (understandably) a substantivalist view of space, which uses an occupation relation that has been spun out into a host of bizarre permutations, though one does not need this framework to consider exotic objects, so we need focus on the object models only without assuming spatial references to be a unique substance. There are those, like Hudson, who advocate a particular terminology for both the relation between space and objects as well as for describing various objects themselves. Although I am happy to use 'occupies' and 'located at' interchangeably, Hudson thinks there is good reason to distinguish them and to prefer the former along substantivalist lines. He prefers to characterise the relationship between objects and spacetime in terms of occupancy rather than either 'is extended in' (because it suggests point-sized objects are nonmaterial) or 'is located in' (because it suggests spacetime *regions* are material) (Hudson, p.2-3). In contrast, while such distinctions have potential merit, there does not seem to be enough evidence to motivate such terminological specificity, and so 'located' and 'occupies' will be equivalently used to reference where an object is.

Parsons gives a considered account of particularly troubling quantum behaviour in terms of 'entension'. This form of the location relation is given to "the phenomenon of a material object being wholly located in multiple places" (Parsons, 2006, p.1). When something is only partly located at multiple spatial places, it *pertends*. Both of these terms have a temporal equivalent: "an *enduring* object is located wholly at each of the times at which it exists; a *perduring* object is located partly at each of the times at which it exists" (Parsons, 2006, p.1). Parsons outlines a narrow lexicon of location, drawing a distinction between an object that is *entirely* located and one that is *wholly* located. I am happy to make use of this vocabulary, not so much because it better elucidates our understanding of location, but rather because it draws out our idea of an object and its relation to space (or spacetime). Borrowing Parsons' terms, we can say that

> *X* is entirely located at *r* iff *x* is located at *r* and there is no region of space-time disjoint (i.e. not sharing a subregion) from *r* at which *x* is located.
>
> *X* is wholly located at *r* iff *x* is located at *r* and there is no proper part of *x* (i.e. a part of *x* not identical to *x*) not located at *r* (Parsons, 2006, p.4).

So long as an object has no proper parts, that is, is an extended simple, it may be wholly located at a variety of spacetime regions without being entirely located at any of them (entended). And according to Parsons, entended objects need not be homogenous, rather they may have what he calls intrinsic distributional properties (the property *being polka-dotted* for example, rather then, say, having parts that are intrinsically dots and parts that are intrinsically not-dots). In this way, differences in an object may be glossed as constituent of the overall distributional property and more ably cover quantum particles.

Although using slightly different terminology, Ned Markosian encourages us to contemplate the similar notion of a scattered object (whose parts are spatially separated from each other), which is seemingly accessible from several angles. We learn fairly early on that objects like hammers and dogs are composed of molecules with 'space' in between them; further, the notion of molecules and atoms come with the idea of lots of space between any matter as well. Markosian extends this familiarity to a mereological classification of objects such that all composite objects are scattered, since, he argues, their proper parts are spatially separated (Markosian, p.405). Under this view, only simples (that lack proper parts) are wholly unscattered. Even if one is not ready to define all composite objects as scattered, the viability of scattered location has given rise to several attempts at classification.

Hudson entertains a far more 'scattered' object in the form of a multiply located object; a multiply located object, *x*, is (i) "located at more than one region, and (ii) *x* is not located at the fusion of the regions at which *x* is located" (Hudson, p.103). That such an object need not be located at the fusion of its parts is perhaps most easily understood through a temporal analogy: if you exist *here* at time t_1 with mass M, and you subsequently exist *there* at time t_2 with mass M, you would not be the fusion of the properties of t_1 and t_2 (such that you had mass 2M). Similarly, Hudson's multiply located object is such that it is simply located in that way and is not the fusion of all those parts.

Such objects need not be entirely located at any one region (though, this may depend on how one defines 'region', for presumably a sufficiently spatially gappy region could encompass a disjoint object that we would consider multiply located). Such an object may have proper parts *or* be an extended simple. In (Saucedo 2006), Raul Saucedo explores at length possible permutations of simple and complex objects located at simple and complex spacetime regions, teasing out the permissibility of gunk and simples. All of these exotic ways an object can be located reflect both our imaginations and the quantum weirdness seen through experiments. Although none of them address the basic mystery of material stuff interacting with spatial stuff (no clearer than Cartesian pineal gland interactions), they have the potential to become a complex canon of reference separate from substantivalism.

7.2 A case study in quantum location

To get a clearer idea of how thinking on how such object types might be explanatorily beneficial to physics, I will use an example that does not rely on a substantival framework. I focus on Parsons' discussion of entensional objects through quantum superpositions and entangled particle experiments (Parsons, 2003)[60]. The set up is familiar, if slightly more complicated than usual; it involves a particle travelling from a source to a deflecting box (in the case of photons, we may suppose the box is a half-silvered mirror), from which point the particle will be deflected, one of two ways, toward detector 1 or detector 2 (appearing at either 50% of the time).

The complexity arises from the different additions one may make by incorporating more deflecting boxes or manipulating the interference (which can arise from a single particle interacting with itself or from impediments placed along the particle path). The orthodox explanation for the particle's strange behaviour is that the particle leaves the box in a superposition of states, that is, the particle is in a sense multiply located along *every* pathway. Even though it is seemingly detected only at one detector in the apparatus—and thus, seems not to have travelled along the other paths that would have led to the other detector(s)—with repetition, the particle's location of detection nonetheless demonstrates a pattern of behaviour most readily explicable by having taken the statistical average of all paths.

Again adopting the orthodox interpretation, we can assume that this paradox of observations not aligning with the supposed process can be explained using the 'Von Neumann strategy', which includes an evolutionary wave 'collapse' that avoids including the entire experiment, observer or the rest of the universe from also entering a superposition of states in regards to where the particle is detected. During the time when the particle is in a superposition, it may be thought to entend or pertend, that is, either the particle will be wholly located at multiple spacetimes, or parts of the particle will spread out and each traverse a path. Parsons argues that the latter account is less appealing for two reasons.

First, it is not at all apparent how the properties are to be distributed across the two half particles as each behaves as if it has "the whole mass of the particle" (Parsons, 2003, p.12). This first criticism could use more support, however, because on the one hand the various properties of the superstates are not well documented nor to my knowledge have they been independently observed, and on the other hand, our lack of a satisfying arrangement of property distribution may be a difficulty for *us* rather than for the theory. Second, and more importantly, pertension when combined with the favoured Von Neumann strategy makes the "half-particles coordinate themselves instantaneously at the moment of collapse" (Parsons,

[60]Also, see chapter 8 for a more detailed account of entanglement.

2003, p.13). That is, pertension gives way to the *very* unsatisfying spooky action at a distance. This latter concern highlights the loss of our explanatory framework should we accept pertension in this case, which *might* be clarified by a new understanding of spatial structure or object-spacetime interface, though is currently mysterious.

Parsons claims to lessen the mystery by adopting entension as an explanation, with the whole particle located at both detectors but affecting only one of them. If he is correct, then superpositions may be perceived as non-homogenous wholly located objects at multiple spacetimes: an electron that undergoes the same deflecting box experiment can be spinning up along one path and spinning down along the other path. Indeed, in experiments involving entangled particles we might see entension as prompting a re-categorisation of the twin particles as "a single entended object, a two-particle, which behaves almost exactly like the mereological fusion of two particles" (Parsons, 2003, p.16). The holistic view of this 'non-separable' quantum state provides an alternative to the 'non-locality' problem; that is, there is no action at a distance or non-local effects because the entended particle is not distant from either detector (and thus, the one it affects).

Parsons is not alone in advocating such occupation relations; for instance, Peter Simons advocates a similar (perhaps coincident) view, if from a different motivation. Simons seeks to reject what he calls the geometric correspondence principle, whereby an object's parts correspond to the parts of the region it occupies, and instead embrace a view of extended simples[61]. When such extended simples occupy a region of spacetime, they occupy all of it, but they need not do so homogenously. That is, an extended simple may have a distributional property (again, e.g. *being polka-dotted*) that is the case all over, even if the intensity of the property (e.g. the polka dot as opposed to the 'background' colour) varies across the subregions of the spacetime region. This idea fits nicely with the theories of location advocated by Parsons and seems to accommodate physical theory well.

Simons argues (though not in great detail) that the non-uniform nature of such simples allows them to overlap, presumably giving rise to forms of co-location. It also allows us to accommodate the empirical interference patterns in describing the 'split' of a beam of photons by a half-silvered mirror and say that the 'beam simple' has gone both ways and

[61] His extended simples principle says that "every physically basic item (simple) occupies at any time an extended region, called its *locus*, but it has no physical proper parts. In particular it has no parts corresponding to subregions of its locus" (Simons, p.376).

redistributed its energy over the new locus. If this seems like a bizarre way to think of one object, it appears neither logically nor metaphysically impossible. Indeed, as noted, our identity ascriptions include spatially separated parts all the time (e.g. 'school', 'family'). What is different here is the potential to have that same spatial discontinuity applied to simples, or having it apply to a spatially separated object that is not spatially separated into *parts* (i.e. it could have parts of any of the spatial instantiations but each instantiation is not a different part).

The substantivalist's occupation relation has spawned (though I don't think was needed to) a rich metaphysical discussion for imaginative ways an object *might* manifest, some of which may be useful tools for physical explanation. It gives us a lexicon and map of ways that relation might be, even if we cannot say much about the relation itself; by analogy, we might not be able to talk about the precise inner workings of a dog though we could say a lot about different breeds. Still, I do not think this overview of locating objects in space has clarified the fundamental relation, something that still needs to be addressed by substantivalists. Although I think substantivalism is not the best model, this creative approach to options once rejected off-hand by the scientific establishment is an important exercise. We need to be cautious of our prejudices toward exotic object manifestations, not only because of the alien quantum world we are now exploring, but because our old models have been shown wanting and embarrassingly anachronistic. Becoming more open and aware of the implications and permutations for objects and their environment in this way has the potential to be of service to modern physics. This, however, is something of a by-the-by for substantivalism, which retains a confusing occupation relation and whose main asset is continuity with physical, i.e. mathematical, models that are not free of mystery either.

7.3 Points, Continua and mathematical interpretation

In addition to the mystery of the occupation relation, points-based substantivalism has the mystery of spatial points and their relation to physical objects. It too comes with benefits—mathematical and explanatory ones—that make the theory so appealing. However, they also make it, for me at least, confusing. Points-based SS inherits these pointy benefits and challenges, though relationalism, dense relationalism or yet some other permutation of a unitary ontology from which both spatial and material substance issue, may be able to avoid these conceptual challenges by turning the geometric talk into a merely instrumental model.

That physics treats spacetime in a predominantly mathematical way, with extensionless points, means we are left to devise how our extended material world fits ‘onto’ this infinite array of unextended points. The substantival merging of mathematical concepts with physical reality raises a concern about how infinite points of space(time) with zero volume could ever compose or interact with anything of volume or create distance. With no *physical* limit set by the size of the spacetime points (because they have none), there is nothing to prevent any two points one may choose from having an infinite number of further points between them—but even accepting mathematical covering limits, does that create *physical* distance and/or spatial separation? Indeed, does that create anything at all?

It may be palatable to think of an infinity of conceptual points, but more confusing to think of an infinity of physical minima that offer no measure. For instance, it is not obvious how varying distances are created between objects when *both* “denumerable and nondenumerable point sets may have measure zero” (Fine, 1973, p.245). Perhaps because our mathematical models enjoy such predictive success, many overlook the strangeness of an abstract but *real* spatial substance interacting with concrete, physically real material substance, but successful or not, it is a strange marriage and one about which we should be wary. Since relativity theory supposes spatial substance to respond and interact with material substance, we are left giving an account of how seemingly abstract points interact with matter.

Indeed, the substantivalist faces something of the Cartesian dualist’s problem of accounting for the connection between different substances, particularly as concerns the mathematical model used to describe space. If, on the one hand, spatial substance is to be likened to the concrete physical stuff of matter, it seems inconsistent to call it a separate substance; to make it a fundamentally distinct *substance* is unwarranted if it is the same stuff as matter. On the other hand, if the spatial substance is to be likened to the abstract existence of coordinate axes, we should be clear how it then can be (if it can) warped by matter when, for instance, the abstract number line is not.

I find this profound physical use of points makes the problem of mathematical interpretation acute; if we take space as real and, say, dimensions as a fundamental structure, are points that which delineate one dimension from another? That is, is it a point *here* with 4 degrees of freedom and a point *there* with 7 degrees of freedom that makes this region 4-dimensional and that region 7-dimensional? The role of spacetime points to dimensional structures is certainly important, though I will explore the reification of points more generally, reviewing some of the issues with integrating the notion of extensionless points with the ‘occupation relation’; that is, I will look at how we are to understand the interaction between the points (or regions) of one substance and the familiar materiality of the other.

The spacetime points of the substantivalist and supersubstantivalist appear to have the volumeless characteristics of mathematical points. If such points are so insubstantial, i) what is the role they play, ii) what makes them *real* and more than instrumental scaffolding, and iii) what is it that provides the specific distances *between* objects? It is not obvious that points can somehow *collectively* yield lengths, nor is it clear how these points relate to objects (e.g. what properties, if any, do they possess? Do they bear properties, say, degrees of freedom? Do they give rise to the appearance of objects as in the case of SS, and if so, how?). It does not seem that point-based substantivalists have adequately addressed these questions, and what follows will be a brief overview of the problems and alternatives that she should take into account. With such concerns in mind I will review some of the problems with points, taking a brief look at the traditional distinction and argue that substantivalists and supersubstantivalists should be concerned with giving an account of them. I will also explore the possibility of a discrete, interval-based alternative, which helps such point-based (or ‘pointillisme’, discussed later) worries, but leaves the question open as to what space is, exactly, since abstract intervals hardly seem much of an improvement on abstract points. I conclude that point-based theories need to take these concerns seriously.

7.3.1 Traditional Account

The substantivalist appealingly suggests we treat space as a real substance on par with material bodies. But where that space is also said to consist of an array of points, we encounter a confusion of categories that dates back to Zeno. Despite substantivalism’s success in aligning with modern physics, I think its general[62] commitment to the reality of points (rather than, say, regarding them as a mere model) means it owes us an account of how its two fundamental ontologies interact.

[62] Not all substantival approaches need embrace this. For instance, William Edgar argues that one can allow space to contain locations without reducing it to a *composite* of locations or points. He takes such an approach to be overtly substantivalist and casts locations as a privileged class of universals which are eternally instantiated and used to individuate instantiations of other universals (Edgar, p.330-3). While an interesting approach, I will assume the standard interpretation of substantivalism here.

For instance, if spacetime is composed of a continuum of points, the substantivalist should be able to tell us how they relate to objects and provide distance length, as well as telling us whether and in what way an entity that occupies these unextended points can have normal properties (or for supersubstantivalists, how they give rise to the concrete world). To that end, I wish to question whether our mathematical account of reality is to be taken at face value (as the substantivalist seems to suggest), or whether it should be viewed as a model only (and perhaps an unhelpful one). If the former, I am particularly concerned with how we are to make sense of extension composed of unextended elements, and in either case I want to know how we are to understand the interactions between extended bodies and spatial/spacetime points. Zeno's metrical paradox and responses to it provide a good example of the conceptual difficulties associated with such interactions, and merits a brief review.

The argument takes four appealing premises drawn from arithmetic and geometry to form an uneasy collaboration that implies that the length of a line segment is 0. I take the construction from David Sherry's account:

1. *Composition*. A line segment is an aggregate of points.
2. *Point-length*. Each point has length 0.
3. *Summation*. The sum of a (possibly infinite) collection of 0's is necessarily 0.
4. *General Additivity*. The length of a line segment is equal to the sum of the length of its parts (Sherry, p.59).

Modern mathematics avoids Zeno's conclusion by creating the concept of limits, distinguishing between countable and uncountable sets, and rejecting general additivity in favour of allowing the summation of an interval's parts to be greater than the whole (that is, the union of the point sets is not a mere arithmetic sum). Adolf Grünbaum explains the seeming paradox in terms of Zeno's metrical ignorance that the cardinality of a set is independent of its dimensional length; the summation properties of topological sets do not require that the *sum* of zero-dimensional sets also be zero-dimensional (Grünbaum, p.294).

Moreover, interpreting length as a Cantorean point set, we find that it need not be "the case that the longer of two positive intervals has 'more' points" (Grünbaum, p.297), and indeed, one may make a continuous mapping of all the points in an interval onto all the points of a square[63]. Thus in mathematics at least, points can achieve things in sets that they could never do on their own. Such developments seem to have left mathematics well clear of Zeno's early concerns, but it is not solely the mathematics with which we are concerned. For the substantivalist, the issue is not so much that mathematics can give an account of the confusion and dispense with it *in its own domain*, but how and to what extent the mathematical model is applied to physical reality.

David Sherry finds Grünbaum's interpretation inadequate and sees Zeno's confusion lying with this conjunction of geometry and arithmetic, rather than lying with a deficient understanding of mathematics. Contra Grünbaum, then, "an uncountable summation of numbers is not inherently problematic, but an uncountable summation of numbers that have been identified with length is" (Sherry, p.62). This kind of arithmetical application to geometry and their conjoined application to reality should give us pause, because it is arguably the real source of the paradox. The restrictions and tools employed by the modern mathematician do not refute this paradox so much as delimit her possible aims. How we should interpret this limitation is not clear, however: whether we are to take unextended points as the literal, physical components of line segments, extension and the stuff of spacetime, or to take them as a useful model only.

Or again as Sherry casts it, it is unclear whether we are to follow Zeno's lead and think of the relation between lines and points in terms of parts and wholes, or whether we follow mathematical set theory and view it as the set-membership relation (Sherry, p.71-2). Indeed, we might reconsider our set-theoretic model and explore, as John Baez suggests, category-based models instead, which "can be thought of as an attempt to treat processes (or 'morphisms') on an equal footing with things (or 'objects')" (Baez, p.178).[64] The blending of mathematical and physical paradigms has certainly proven fruitful, but it is partly in virtue of this success that it is so difficult to separate the model from genuine reality. We may find that "although, as mathematics and physics have shown, the grammar of atomism and the grammar of lines and points can be profitably joined, the latter can never by fully subsumed under the former" (Sherry, p.71).

[63] More generally, through his work with infinite sets Cantor proved (*mathematically*) that "*n*-dimensional space has exactly the same number of points as a 1-dimensional space" (Shapiro, p.66).

[64] "A category consists of a collection of 'objects', and for each pair of objects *x* and *y*, a collection of 'morphisms' from *x* to *y*…in category theory, an object need not have 'elements' or any sort of internal structure…What really matters about an object is its morphisms to and from other objects. Thus, category theory encourages a relational worldview" (Baez, p190).

This type of distinction can be found in Aristotle as well as Zeno, where the former suggests that "there is actually an infinite number of divisions in an interval, but that these divisions are not to be understood as *parts* of the interval" (Edgar, p.329, emphasis added). Similarly, Nerlich argues that clarity can be found in mereological terminology: "the only parts of continuous or merely dense space are its (proper) intervals; it is a sum only of these. Points are not parts of space nor is a space a sum of points. Points are members of intervals, not parts of them…points are in spaces as members are in sets, not as parts in wholes" (Nerlich, p.175). Nerlich thus appears to reject spatial points as constituents in favour of spatial intervals, along which one can locate an infinite number of points—as we would expect to find along any interval—that are nonetheless not *parts* of that length. Points can be 'found' anywhere, much like the number seven, but when constructing chairs or puzzles or spacetime distance, they are not any *part*.

Further, while we can *conceivably* carve up a line an infinite number of ways, we can only *actually* divide it a finite number of ways. This is very much a difference between points and physical bodies, and the logical operations we can apply to each kind of entity. For instance, we might assume that a dense continuum has axioms that can be satisfied in a domain of points while physical bodies require a different sort of logic altogether. José Benardete follows Aristotelian lines when he argues that "the categorical distinction between points and bodies is so ontologically profound that it explains why it is that the axioms of absolute continuity may be satisfied in a domain of the one but not the other" (Benardete, p.425). For Benardete, the points of conceptual or mathematical space are mere possibilities, many (even an infinite number) of which can be actualised, but not all of them; the actual world of bodies is discrete and does not follow the axioms of absolute continuity. He concludes that there is no one-to-one mapping of actual bodies to points in the continuum, and we should not be surprised at this restriction:

> The distinction between the discrete and the continuous proves to be derivative from the deeper distinction between the actual and the potential. To be *actually* continuous is to be *capable* of being divided in more ways than can ever be realized. Thanks to the fact that potentiality is necessarily richer than actuality, we can understand why it is that the axioms of continuity cannot be satisfied in any domain of bodies (Benardete, p.426).

Thus, while we may reap the organisational benefits of the number line we are nonetheless left with the curious task of trying to pin extended actual objects 'onto' an infinite range of unextended points (potential objects?) that somehow constitute the various spatial separations we perceive. What, then, could 'being located at' or 'occupying' mean when we try to situate an object in space? Such an unintuitive marriage should have very good support for its acceptance, and one that could usefully distinguish that sort of abstract from other, 'less real' sorts of abstract. If spatial substance is made of points at which we are located, then what is to stop us from being located along abstract number lines at point 2.36 or point 4388? It is not clear that there is anything more than our arbitrarily determined coordinates, or a relational matrix of other objects that determines exactly where (in some absolute sense) an object *is*. Points-based substantivalism needs to explain this interaction, and with something more than claims for primitiveness; such attempts did little to make Cartesian dualism palatable and I see no reason for being less lax in this case.

7.3.2 Modern Concerns

Modern engagement with mathematical axioms and points-based ontologies (from philosophers like David Sherry and Jeremy Butterfield) has given rise to similar paradoxes contrasting the available intuitive operations on *space* against the available operations within *mathematical systems*. For instance, locating properties like *mass* and *charge* to point-sized particles leads to problems like infinite density (Simons, p.373). The apparent absurdity of applying such theorems to the physical realm leads the like of Peter Forrest to reject the standard view of a points-based substantivalism and side with Jeffrey Russell who suggests that points my simply be temporary scaffolding to be jettisoned in latter theories (Russell, p.249).

Both general relativity and quantum theory agree in their use of points in mathematical models, but as Jeremy Butterfield and Christopher Isham note, "one needs to respect the distinction between a (putative) physical spacetime point, and an (undeniably postulated!) point in a mathematical model of spacetime based on standard set theory" (Butterfield and Isham, p.52). That is, mathematical models may only be taken so far and require clear rationale for doing so in each case. They cite a reason for our readiness to reify through our tendency to formulate theories where points are postulated "at the beginning of their formalism; the rest of physical reality being represented by mathematical structures (vector, tensor, and operator fields etc.) defined over the set of points" (Butterfield and Isham, p.52). However, they argue, the theories need not assume such mathematical objects as representing spatial points, rather the theories may take those mathematical objects to represent, say, fields. Indeed, we might formulate the theories "in such a way that the fundamental mathematical entity is not the set *X* of spatial points – on which *fields* are then defined – but rather a commutative ring, on which spatial *points* are then defined: viz. as maximal ideas" (Butterfield and Isham, p.52). The range of alternatives to reified points afford substantivalists plenty of options, and given the unclear theoretical interface between material and spatial substances, it appears that they would do well to explore the options.

An additional problem lies with the Leibnizian concern for distinctions without a difference (or 'symmetry transformations'), as was seen in the 'Hole argument'. Butterfield and Isham argue that this problem arises with any theory of general covariance and spacetime points as objects, as the combination implies a radical indeterminism that should prompt us to reject the physical reality of spatial/ spacetime points (Butterfield and Isham, p.54). This ontological interpretation of spacetime points can certainly complicate matters, but adopting a more structural definition may ease the issues; to keep philosophical claims subservient to empirical ones, we are compelled to think of spacetime points as indiscernible, such that they could exchange properties so long as the overall structure is preserved. Even if one argues for the discernibility of such points through a sophisticated substantivalism, one may need to appeal to the *relational* structure of the metric as a means of individuation rather than a primitive haecceity.

Arguably, "the use of real numbers (and similarly complex numbers) in quantum theory in effect involves a prior assumption that space should be modelled as a continuum" (Butterfield and Isham, p.85). Further, it may be that this bias slows our construction of a discrete structure at the Planck scale that would more aptly capture reality. Indeed, the inability to completely unify general relativity with quantum theory has prompted some to suggest altering the mathematics we use to better incorporate discrete models. For instance, "standard mathematics is based on set theory, and certain aspects of the latter (for example, the notion of the continuum) are grounded ultimately in our spatial perceptions. However, our perceptions probe only the world of classical physics – and hence we feed into the mathematical structures currently used in *all* domains of physics, ideas that are essentially classical in nature" (Butterfield and Isham, p.85). This is not to say we should dismiss classical models, but only that our biases may be more prevalent in this area than realised. Moreover, there are classical reasons that we might reject a point-based model.

The notable limits of the partnership between mathematics and physical interpretation have been discussed by Butterfield in his several papers against *pointillisme*, wherein he argues against the "doctrine that a physical theory's fundamental quantities are defined at points of space or of spacetime, and represent intrinsic properties of such points or point-sized objects located there" (Butterfield, p.2). Butterfield's account follows the conclusions of Part I in embracing a more extrinsic view of spacetime points whereby they cannot support the property attributions of many physical qualities, specifically those of classical mechanics. It is worth noting the four main concerns he raises in this respect, both as a way to highlight the drawbacks of such point-based models (some of which I discussed) and to add his particular concerns to the general complaint.

Firstly, Butterfield argues that pointillisme violates, or at least must concede to classical mechanics in regards to the binary relation of 'occupies', which "presumably brings with it extrinsic properties of its relata: it seems an extrinsic property of a point-particle (or a continuum, i.e. a continuous body) that it occupy a certain spatial or spacetime point or region; and conversely" (Butterfield, p.11). For instance, the need to go beyond the summation of points in a line to get the property of 'length', which is extrinsic to the points, is at odds with pointillisme's claim that the fundamental qualities are intrinsic to points.

Secondly, the spatial structure of classical mechanics "involves a complex network of geometric relations between, and so extrinsic properties of, points" (Butterfield, p.11). Specifically, Butterfield argues that the geometrical demands of attributing vector properties (a tangent vector with its attendant space and a metric tensor) to points in order to define curvature cannot reasonably be intrinsic since they are directional and relational. Citing both Denis Robinson and pre-1993 David Lewis, Butterfield argues that, though uncomfortable, the conclusion results from the intuition that a zero-dimensional point could not instantiate a vectorial property (Butterfield, p.22). If true, then it is yet another way that pointillisme contradicts—the very useful—classical mechanics. Thirdly, Butterfield argues that reference to "instantaneous velocity or momentum of a body...is temporally extrinsic to the instant in question, since for example it implies the body's existence at other times" (Butterfield, p.12). Given the union of space and time into spacetime, this further element of extrinsicality poses a problem for pointillisme and removes part of the appeal for a point-based substantivalism, as does Butterfield's final point. Fourthly—and briefly, he argues that classical mechanics is not, in fact, formulated in terms of points, but rather in terms of *regions* (Butterfield, p.12), and thus is notably divorced from the more acute problems of abstraction that come with pointillisme.

Butterfield's complaints echo some of the issues mentioned earlier, all of which make the adoption of a point-based substantivalism unattractive. First, we looked at some of the larger structural concerns dictating how an abstract geometry of points interacts with the concrete physicality of material substance, which offered no clear answer. In this we explored some of the traditional debates dating back to Zeno and including the 'solution' of modern mathematical 'covering laws', which nonetheless seemed to miss the crux of the paradox. The promising alternative of a discrete approach was also briefly reviewed, followed by a litany of challenges and/or failings of the point-based model.

The above discussion suggests a substantivalism that is region-based as a more promising alternative to pointillisme, but it also suggests that there remains a pronounced disconnect in the substantivalist's model between the non-physical substance of space and the physical substance of matter and energy. If each substance deserves such a classification, it is frustratingly unintuitive to explain how they interact and what we are to make of the *reality* of the former. If, on the other hand we discover that by space we actually do mean something like 'energy field', then space and matter are not obviously two distinct substances since intuitions go both ways about which ontological category they belong to. Admittedly, this depends on how one conceives of spatial substance, but I wonder whether—if we are honest with ourselves—we might be driven to a more unified (perhaps *super*substantivalist) picture.

7.4 Conclusion

The traditional substantivalist approach has proven fruitful in conceiving and developing modern physics, not least because it maintains the geometrisation so common in that discipline. Substantivalism also leads us, if serendipitously, to consider an explosive range of ways to scatter or centralise bits or all of an object through an array of spatial partitions, which may prove useful models for physics. I think there are real problems with the standard account, however, including the basic doubling of substances, the phenomena that it fails to help explain, the mysterious 'occupation relation' and its traditional use of points. There is room within the theory to accommodate point-based concerns (adopt regions instead) and perhaps approaches to various physical phenomena, though more work needs to be done in support of these, and a good deal more to address the interaction of independent fundamental substances.

Substantivalism is not the only option of course, and its offspring theory, SS, avoids some of the conceptual confusions while maintaining the mathematical tractability. Like relationalism, it gives a parsimonious ontology that does not need to incorporate the mysterious occupation relation. Like substantivalism, it can adopt the working terminology and models of modern physics in describing distances, fields and spatial orientation. The conceptual challenges attendant to adopting a point-based spatiotemporal structure are, I think, significant however, and give good reason to pursue more discrete relationalist models. Similarly, it appears compelling to explore other formulations of a single ontology theory that does not prioritise either space or objects.

That is, physical phenomena are suggestive of a single stuff, but give us no reason to assume that substance is either of the ones we traditionally delineate in substantival theories. Indeed, dense relationalism, which adopts fields and all energetic minima, may be as well off as SS in explaining the data and satisfying theory desiderata. To this end, I conclude that current substantivalism, both regions or points-based, should be put aside in favour of developing monistic ontologies, particularly ones that can clearly articulate the physical interpretation of mathematical theory. Dense relationalism and relationalism are both up for ongoing review to make them sufficiently compatible with modern physics to be dominant models. SS, both regions and points-based, has more work to do with interpreting the theory and mathematical formulism (particularly with the latter version). It is thus relationalist and supersubstantivalist theories that appear most compelling in regards to the discussed phenomena and philosophical concerns. In trying to address such issues with standard substantivalism, we continually return to the problem of space itself, of its characteristics and structure—and of our expectations failing spectacularly in the face of experimental results—and this issue will be the focus of Part III.

PART III: Space in Itself

We typically use the term ‘space’ in a dizzying number of senses that encompasses everything from a conceptual tool (e.g. for separating objects), to the expanse between planets, to an array of unextended points on which all matter is pinned. In the sciences some “find it useful to keep the concept of space rather fuzzy because it can imply many things for which we have no other terms” (Yau, p.18). In each respect, space and its modern marriage with time as spacetime is viewed as a fundamental aspect of the universe, and although its attributed properties have altered over the last century, space just seems to have room to accommodate them. As a conceptual tool space is used as a realm for manipulating objects or mapping the possible histories of states and values in Euclidean and Phase space, respectively. In most everyday discourse, space remains a vacuum, a void surrounding distinct objects, while to modern physics ‘spacetime’ is a dynamic, engaging entity, which may even be an emergent property of some grainy, mysterious quantum contortions. I am interested in ‘space’ *per se*, though its century-long association with ‘time’ has made talk of ‘spacetime’ often commensurate with ‘space’, and I will use the terms ‘space’ and ‘spacetime’ interchangeably unless otherwise noted.

Space is generally associated with distance—we expect that more space between objects amounts to more distance between them—and is thus used to separate and locate objects, logically and physically (while time is used for analogous measurements of duration). Separation is what we commonly use to distinguish one billiard ball from another—if the two balls were in the same place at the same time, we would suspect there to be just one ball. However, in the quantum world, separation does not appear to be determined (solely, if at all) by spatial distance. Determining the fundamental constituents of either matter or space has proven difficult, and part of our response has been to give explanations that rely on nonseparability, that is, to move away from classical conceptions of space’s role. In addition to spatial separation, physical space is characterised as notably different than abstract spaces and as something with structure, though what these aspects amount to is far more vague. In this, I am particularly interested in the much neglected topic of dimensionality. Higher dimensions run riot through many of our best theories, but philosophers and physicists remain unsure of what dimension is or how we are to treat it.

Thus, in trying to better understand aspects of space not captured in the space-object framework discussion of Part II, I first question whether we can assume that space separates objects—looking at instances of nonseparation and what we have to give up in adopting that framework. Second, I look at some options for what we think makes a space *real*, in the physically concrete way. Third, I look at the confusion surrounding dimensionality and its possible formulations. Fourth, I explore the uses of dimensionality, including profound roles in shaping our best physical theories, and finally, I look at realist and non-realist interpretations of dimensions. In pursuing dimensions—often seen as spatial structure—it seems a more tractable approach to better understanding space than diving in for its essence (lesson learned from Part I), though it too raises fundamental questions (e.g. about what sort of ontology is adopted). I offer more questions than answers in the latter section, but in this case it is important work too.

CHAPTER 8: Physics and Non-separability

Incorporating the broad conclusions of earlier chapters (e.g. that the distinction between object and environment is unclear and perhaps fundamentally so) I want to examine the interplay of physical theories with our expectations of space in a bit more detail, questioning our belief in clearly defined physical space. I will explore several suggestive physical examples of a unified fundamental ontology in a continuing bid to refine and update metaphysical ontology and to emphasise how suspiciously elusive 'space', as separate from objects, really is. This examination is meant to build on Part II's concern that substance dualism is problematically mysterious, and to reveal how little purchase we have on 'space-in-itself'. First, the concept of locality, through 'entanglement' will be taken up to examine objects in space and whether physical space always provides the separation we assume it does. Second, the permeability and homogeneity of space will be reviewed in terms of quantum tunnelling. Third, I will look at the blurring of material and spatial substance through the double-slit experiment and, finally, I will review the implications of this physics for separability.

8.1 Objects *in* Space: Entanglement

Classically, object properties are thought to be local, but modern physics makes it hard to say which properties an object has when we cannot pin it down and find a lack of definite observables. One of the best examples of this break with the behaviour of classical objects—and perhaps another reason to suppose spatial and material substances to share a deeper connection—is entanglement, whereby our spatial expectations seem confusingly opposed to experiment, suggesting that spatial separation does not have to mean causal separation. Indeed, a great deal of attention has been directed to this quantum phenomena of entanglement, particularly because it appears to violate causal locality; that is, "we get a counterfactual0supporting causal connection between the…[particles] which cannot be explained by a common cause" (Maudlin 2002, p.147)[65].

Entangled particles manifest correlated behaviours at the same time despite being spatially separated, suggesting that "intervening space, *regardless of how much there is*, does not ensure that two objects are separate" (Greene, p.80). And unless we are willing to embrace a theory of hidden variables that programme or connect the pair, we are left with the orthodox interpretation of nonlocality. As Peter Gibbins notes, being *nonlocal* "can be a matter of nonlocal forces, of nonlocal correlations, or of physical holism…[at least] in the second and third senses of nonlocality (insofar as they are really separable)…quantum mechanics is a nonlocal theory" (Gibbins, p.116). I will briefly review the experiments in question to better understand the metaphysical implications and see whether we should accept such standardly perceived instances of nonlocality as exceptions to an otherwise robust theory of objects and space, or whether we should be compelled to re-evaluate our assumptions and entertain a holistic theory. I encourage the latter.

Briefly, entanglement describes a type of relation between particles or molecules that holds after they have interacted and separated, whereby the pair creates a quantum superposition with each member described by the same quantum mechanical state *until* a measurement is made. So when a pair of photons are produced (see Figure 2), the measurement of one member communicates the measurement of the other member, and moreover is thought to *determine* the state of the unmeasured member (Maudlin 2002, p.22-4). Several versions of the entangled pair experiment can be performed, involving photons or electrons, that generally test the spin polarisation.

The experiment as so conceived was explained by Einstein and his graduate students Boris Podolsky and Nathan Rosen as simply indicating our ignorance of further (hidden) variables that do connect cause and effect; in other words, quantum mechanics is incomplete. In a paper to this end (EPR), Einstein, Podolsky and Rosen had argued that even though we may not be able to measure it, the electron *does* have a definite spin around each of its axes.

[65] Some authors (e.g. Redhead 1987) doubt the connection should be causal, but (Maudlin 2002) effectively argues for understanding it causally, which need not permit superluminal *signaling* (Maudlin 2002, p.154).

Little progress was made in dismissing this concern until several decades later when John Bell analysed the probabilistic outcomes of correlations *assuming* hidden variables. He concluded that, whatever the hidden variables were, the particle pair would have to display a certain probabilistic agreement in measured spins to support EPR's hypothesis.

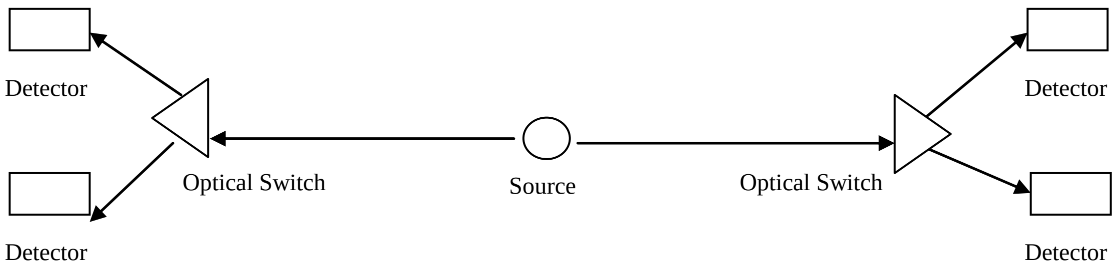

Figure 2. General diagram of the EPR set-up

Bell's analysis of the EPR dilemma was tested over a number of years, but likely the most famous experiment was performed by Alain Aspect and his team in the 1980's. In it, a calcium vapour is made to fluoresce, causing electrons to fall to their ground state and emit a pair of photons in opposite directions. The photons are then measured for their spin (though the same principle would hold for other entangled properties like velocity and position) along a certain axis by two detectors set 13 metres apart (and thus at such a distance that light cannot travel between them to relay any 'messages' about the other particle in time)[66]. Therein,

> the polarization of the photons individually shows no preferred direction: for any randomly chosen direction θ the photons will pass a polarizer oriented in that direction half the time. But although the photons individually show no particular polarization, the pairs exhibit some striking correlations. Roughly, each member of a pair always acts as if it has the same polarization of its partner (Maudlin, p.12).

Theory predicts and experiments confirm that whatever value one detector measures, the other will detect the corresponding opposite, such that we may *know* the value of one upon measuring the other particle at space-like separation. The detectors may be further manipulated to randomly vary the measured spin axis. According to Bell's calculations, for EPR to be right, the detectors would have to agree more than 50 percent of the time.

[66] The experiment was undertaken again in 1997 by Daniel Salart and collaborators with the detectors placed 11 *kilometres* apart (see Salart et al.). With the results unchanged, physicists confidently expect such entanglement to prevail across the length of the universe (Greene, p.115).

However, they do not agree more than 50% of the time, thus indicating the violation of Bell's inequalities and a flaw in the traditional reasoning employed by EPR, which is generally agreed to be the assumptions of locality and separability[67]. Orthodox quantum theory further explains this process by arguing that until the time of measurement, the particles were in an indeterminate state; their wave functions only 'collapsed' (across the universe)[68] to a determinate value with the experimenter's interactions.

So not only do the particles display inexplicable correlations, but up until the time of measurement there are no determinate properties to measure. Although the Bohmian[69] and orthodox (Copenhagen) interpretations diverge on this point, they both agree that locality is violated—that the effects of the measurement on one particle "creates a state of affairs" (Maudlin 2002, p.87) at the other particle faster than any known causal process. Standard quantum theory has been at pains to describe what exactly occurs in this situation, but the general understanding is that the universe is not local, and that "*entangled particles, even though spatially separate, do not operate autonomously*" (Greene, p.114). That is, spatial separation need not mean causal separation. This has significant implications for any revised theory of the relations between objects and space, particularly as the extent of entanglement can blur distinctions between the two. For, in some sense even "the vacuum state of a quantum field is entangled…with certain spacelike separated regions of Minkowski spacetime" (Healey 2009).

This nonseparability has also strongly motivated various theories of ontological holism that recast the emitted pair as a single effect occurring at the left *and* right wing of the experiment; "in other words, the effect is the 'disentangling' of the particle pair; that object is becoming *two* particles" (Lange, p.292). Like Parson's conception of an entended particle, under this approach, measurement did not bring about two wave-collapses, but a single wave collapse into two particles. Lange notes that this approach has important connotations for how we divide up the universe into objects, which may be radically refitted to include space-

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[67] Mark Silverman usefully distils their assumption by noting that, while "admittedly arbitrary, EPR adopted as a reasonable definition of reality the criterion that: "If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity" (Silverman, p.46).

[68] Wave collapse as an interpretation of events remains controversial as it "does not emerge from the mathematics of quantum theory; it has to be put in by hand, and there is no agreed-upon or experimentally justified way to do this" (Greene, p.119).

[69] Alternative theories such as the Bohmian view of quantum mechanics have offered alternative accounts (that both claim that Schrödinger's wave function fails to represent *all* physical facts and employ hidden variables) that nonetheless adopt some form of nonlocality (e.g. see Goldstein and Teufel 2001).

like separation (Lange, p.297). In practice, it is only the *pair* of particles (rather than either particle individually) that has “sharp properties: zero total linear momentum, zero total angular momentum…Experimentally, there is no way to probe the pair of correlated photons to determine the properties of its constituents without destroying the correlations” (Silverman, p.52).

However, even if we treat the entangled pair holistically, the opposing traditional conception of individuation as well as the seemingly separable and individual nature of the particles when *not* entangled, both encourage a traditional ontology that rejects such holism (or at least its wider application). Michael Dickson, among others, rejects in (Dickson 1998) the holistic approach that the two particles are really one object, as “it is not clear how one is to keep the disease from spreading. Why are our apparatuses not also ‘parts of’ holistic objects?” (Dickson, p.156). In response, some holists are happy to accept the extension of holistic objects to include cosmological scales (which, much like the notion of a field, have a sharp decrease in efficacy away from the relevant ‘centre’). And in a less overt holism, some, like Neils Bohr, argue that speaking of quantum phenomena without the apparatus framework is nonsensical.

Where physical holism is rejected, one is generally left without satisfactory explanations and with suspicions that the particles *somehow* remain in communication. Rejecting causation is understandably anathema to science, which has created itself on causal foundations and proven it a wildly successful and intuitive paradigm, and further it is unclear what could take its place. So rather than giving up our model for causation we might press on with such beliefs of hidden contact, or we might see our models as inadequate; “quantum correlations violating Bell inequalities simply happen, somehow from outside space-time, in the sense that there is no space-time explanation for their occurrence: there is no event here that somehow influences another distant event there” (Salart et al., p.861).

This observed departure from classical strategies at explanation reflects the very unclassical behaviour of the quantum correlation (or ‘interactive force’) itself, in that 1) it does not diminish with distance, 2) it discriminates with the particles it affects, and 3) it operates faster than light (apparently instantaneously). This behaviour is not a product of the laboratory, and “non-locality is very likely the *rule* rather than the exception for quantum mechanical systems. Entanglement of systems occurs…in the course of quite typical interactions among quantum mechanical systems” (Dickson, p.129). While this raises the spectre of universal entanglement (as the set of all interacting quantum systems), it is commonly dispatched by noting that it is likewise interactions that *disentangle* particles and give them determinate values. The tremendous number of interactions occurring every instant in the universe may thus create and destroy many pairings, preserving determinate values in some sense if not locality.

Entanglement thus presents a view of objects that disregards the standard limiting role of space; despite kilometres of spatial separation, two seemingly discrete particles display correlated behaviour, and it is not clear that the paradox lies with the quantum phenomena or with our understanding of space and its relation to objects. Mark Silverman has located the fault with the human approach, arguing that

> The 'paradox' is primarily one of unfulfilled expectations of philosophical preferences ('objective reality', 'locality') and deceptive physical images evoked by semantically poor labels ('state-vector collapse', 'instantaneous action at a distance'). In its present form – and most likely for any future incarnation – quantum theory does not describe single events, but only the statistical properties (count rates, correlations, cross-sections, etc.) of numerous events (Silverman, p.53).

If what is required is merely a shift in perception and expectation, then there may be ways to salvage locality or at least address this measurement issue. Arthur Fine even argues that simply assigning values in a different way can render quantum mechanics local. He thinks we should note that Bell's inequalities and variants of it are "not a 'proof of nonlocality'. It is a proof that locality cannot be married to the assignment of determinate values in the recommended way" (Fine, 1999, p.10). However, such assignments are not so easily accounted for, and turning to non-standard quantum theories is no guarantee of locality, though they may solve other problems. For instance, adopting a Bohmian mechanics arguably avoids the measurement problem while offering "progress toward a coherent treatment of the classical limit…and the meaning of the numerical output of a tunnelling-time experiment…The price tag for all of this is non-locality. But such non-locality is arguably unavoidable in any empirically adequate quantum theory" (Cushing and Bowman, p.92). So while there are other options that merit investigation, the orthodox interpretation of quantum mechanics and indeed the *observed* behaviour of particles compel a deeper analysis of our assumptions about what space is and how it relates to objects, since its status as a standard means of separation is challenged.

8.2 Quantum Tunnelling

While entanglement has received much attention as evidence of quantum nonlocality, it is not the only phenomenon that transgresses our assumptions about the relationship between space and objects. Quantum tunnelling also appears to violate our causal sense and challenge the traditional 'density' of spatial distance. Broadly defined, quantum tunnelling occurs when a particle crosses a region of space that it should not have the energy to cross, often at apparently superluminal speeds. That tunnelling occurs is widely agreed, but the claims for time taken are contentious, leaving many to respond that superluminal tunnelling claims are only a confusion of interpretation. Physicist Günter Nimtz is among the strongest proponents of superluminal interpretations of quantum tunnelling, arguing that his experiments demonstrate "that there are spaces which could be crossed in an imaginary time, i.e. a time that cannot be measured by electrons, photons, atoms or even molecules" (Nimtz and Haibel, p.79). It is this seemingly instantaneous jump of the particle—or rather wave packet—that violates spatiotemporal (and spatial) locality—yet another relic of classical models.

I will briefly review the predictions and experimental results of this phenomenon as an example of the unexpected interactions between space and objects. Following the discussions in chapter 7, tunnelling offers a valuable model for substantival theories of objecthood and location. For supersubstantivalists and relationalists, it may encourage the 'object as property bundle' view (which may not always instantiate with spatiotemporal or temporal contiguity, respectively). Focusing on substantivalism, however, there is a real possibility that the object/ space relationship is flexible in this way *because* they are interchangeable and of the same substance; we might not have lost the object, but only transformed it into spatial stuff and back to material stuff. In this, I think the phenomena encourages us to consider space in non-substantival terms with tunnelling suggesting a breakdown of the classical roles of object and space (particularly the idea of spatial separation and causation being spatiotemporally contiguous).

Experiments involving tunnelling employ a variety of devices to produce 'forbidden energy gaps' through which the incoming particle/wave packet should not have the energy to traverse. Such devices include double prisms, photonic lattices or undersized wave guides (that bottleneck to discriminate certain frequencies), and each may produce barriers of varying lengths. In a double prism scenario for example, although the incoming beam to the first prism should be totally reflected, the placement of a proximate prism (some centimetre away, say) creates a ‘frustrated total reflection’, where a small part of the beam “tunnels as evanescent modes through the air gap from the first into the second prism” (Nimtz and Haibel, p.86). Although we are unable to observe the process within the barrier, it is assumed to take the form of such evanescent modes that can be thought of as virtual particles or field modes with no real wavelength and negative energy (Nimtz and Haibel, p.103). The signals used in most tunnelling experiments are photons for greater precision, which allows that “the results could then, through mathematical equivalence, be transformed to electrons and generally to all particles” (Nimtz and Haibel, p.85).

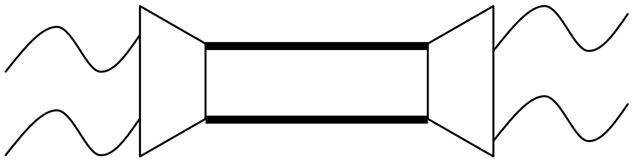

Figure 3. A model of an energy barrier, where the long thin rectangle presents a smaller area than the frequency should be able to enter.

Particularly problematic in the scenario is the temporal duration of transmission, which can be measured by the difference between the time when the peak of the transmitted wave packet leaves the barrier and when the peak of the incident wave packet arrives at the end of the barrier. Surprisingly, the tunnelling time of these modes can become independent of the barrier length (Nimtz and Haibel, p.112) in a process known as the Hartman effect, which has been found in multi-dimensional barriers (Bandopadhyay, p.267). As the energy of the evanescent mode, or field, exponentially decays within partially opaque “barriers, the tunneling time evaluated either as a simple ‘phase time’…or calculated through the analysis of the wave packet behavior…becomes independent of the barrier width...This implies that for sufficiently large barriers the effective velocity of the particle can become arbitrarily large, even larger than the light speed in the vacuum” (Bandopadhyay, p.267). Such speeds are reached because the travelling wave-packet appears to require only one oscillation period to traverse gaps—any gaps. All this amounts to the possibility that there is a flexible relation between objects and space, perhaps allowing a borrowing of energy from the latter in certain situations.

The signal strength (if not the time duration) is thus affected by the traversed barrier length, but it can also be influenced by surrounding barriers and the differences in potential of passing through any one of them. One can construct a branching network of barriers that alters the signal in unintuitive ways, including what appears to be time advancement (with the peak pulse arriving at the start *after* passing through the barrier). In a response characteristic of the 'sum of all histories approach'[70], whereby the particle's path is viewed in phase space as taking all possible routes, the 'phase time' and its saturated value at any side branch feels the presence of barriers in other spatially separated branches (Bandopadhyay, p.272). This effect is perhaps not so surprising given observed quantum behaviour in other situations; indeed it is a, by now, familiar indication of quantum nonlocality. But familiarity in this case gives us no special purchase on understanding the object-space relation, and it is not just this relation at stake, but issues of causation, relativity theory and information transmission.

For instance, repeat experiments from multiple labs have demonstrated apparently superluminal tunnelling using dielectric mirrors (Chaio et al. 1995 and Spielmann et al. 1994). As if zero time were not problematic enough, concerns of backwards causation have been raised following experiments where "the peak of a pulse arrived at the exit of a medium before it had reached the entrance. Consequently the spread of the peak traveled in the opposite direction" (Nimtz and Haibel, p.15). Most scientists argue that this data does not violate primitive causality in relativity theory (Nimtz and Haibel, p.105), but whether it violates special relativity in general is less clear—largely because it depends on one's interpretation of just what the theory prohibits[71]. Philosophers like Maudlin, who have already conceded superluminal causal connections and information transmission through the violation of Bell's inequalities concerning entangled particles, may be more inclined to find compromises between the phenomenon and theory.

Although Nimtz does not appear to follow Maudlin's rigorous definitional standards for 'signal', he notes that "experiments have shown that superluminal velocities are indeed possible and can transmit signals and thus information" (Nimtz and Haibel, p.117). For instance, an experiment tunnelled an extended pulse of information—a piece of Mozart's music—on a microwave carrier at a recorded 4.7 times light speed (Nimtz and Haibel, p.104-5). While there was no recorded signal in the strict sense that might enable backwards causation, Nimtz claims that there was superluminal information transfer, which Maudlin argued is implied via quantum entanglement. In this, one sees that it is not just the

[70] Aptly described by Lisa Randall, after Feynman: "in quantum field theory, everything that is not forbidden will occur" (Randall, p.228).

[71] Maudlin argues that the fundamental feature of special relativity is the invariance of the speed of light, which does not explicitly prohibit superluminal velocities, indeed, depending on the structure we attribute to spacetime, all manner of superluminal transmissions may be allowed (Maudlin, p.112-6).

spontaneous permeation of quantum wave packets through a forbidden space in zero time, but the controlled transmission of information. Our current theories of space, causation, matter (or energy) propagation and objects shed little light on this phenomenon, which might be better analysed under alternative frameworks.

Nimtz's conclusions are by no means universally accepted, however, with opponents like Herbert Winful arguing for a less exotic interpretation. In particular, he takes issue with Nimtz's definition of 'transit time' and with his assumption that the incident particles are the same particles that exit the barrier. Aided by mathematical simulations, Winful argues that the experiments reveal something of a domino effect in that there is a trapped standing wave already extant in the barrier that is in some sense pushed by the incident wave front and made to dispel photons at the other end of the barrier:

> once the exponential standing wave (evanescent mode) has been established within the barrier, the newly arriving light modulates this stored energy and thus the amount of flux that escapes through the boundaries…Because of the multiple reflections, once any light enters, it gets all mixed up, scrambled, so that we cannot look at the transmitted pulse and say, aha this portion of the transmitted pulse entered the barrier at such and such a time (Winful, p.66).

If the light gets as unrecognisably scrambled as Winful suggests, then it seems overly presumptive to call the process 'tunnelling' at all (perhaps the quantum 'knock-on effect' is more apt), but it also does not seem to account for the transmission of the sent information as easily. Making a conservative compromise between Nimtz's and Winful's views that accepts *sub*luminal tunnelling, we might still inquire about the nature of the object's spacetime traversal.

Here, one of the central issues is what makes some property 'spatial' or 'material' is unclear. The distinction does not appear as obvious or intuitive as it does from an armchair, and if we find the properties of each 'substance' to be indistinguishable then we have very little cause for supposing they really are distinct substances. This concern closely allies to the disparity between our *expectations* of both a homogenous space that proportionately separates distant objects, as well as particle-waves being restricted to proportionate and homogenous negotiation of spatial extent. That is, we do not expect objects to be able to leap from one region of space to another without paying their dues and passing through the intervening space. There may be familiar explanations for this phenomenon, but it is possible that there may be something else at work like a much more fluid relation between particle and space derived from a singular substance, or a different permissibility of interactions at the quantum level.

8.3 Double Slit Experiment

We first met wave-particle duality when exploring some of the difficulties presented by indistinct object boundaries. For many of the same reasons that it was problematic for attributions of intrinsicality, wave-particle duality is interesting for addressing the relationship between objects and space, both in revealing apparent non-locality for the objects and in the permissibility of space in 'locating' objects. One of the most iconic ways of perceiving this dual nature is achieved through the double slit experiment, wherein a single particle or a beam of them (photons or electrons) is directed toward a barrier with two slits and onto a detector screen. The particles display an interference pattern (vertical bands of absorption) indicative of colliding waves, and they manifest this pattern whether emitted as a beam en masse or as individual particles over time. While most of the specifics do not concern us here, the relevant issues to which we should be attentive are 1) the way space 'hosts' objects, and 2) the way objects appear to negotiate a 'phase space' of all possible routes in their actual behaviour.

Part of the difficulty in determining how quantum objects interact with space is that we seem to destroy that relationship in our act of observation. The coarseness of our measurements means we can only test (and roughly at that) the beginning and end of a trajectory and never the process as it is in itself. In the double slit experiment we do not know exactly how and in what way the electron negotiates the intervening space, only something of how it negotiates our measuring apparatus. Nonetheless, the results suggest nonlocal interactions and an engagement with space that seems to happen only at microscopic levels: "according to quantum mechanics, each electron's probability wave *does* pass through both slits, and because the parts of the wave emerging from each slit commingle, the resulting probability profile manifests an interference pattern, and hence the electron landing positions do, too" (Greene, p.179). These probability waves are unusual in two ways; one, they are (generally) not meant to be material, that is, to consist of matter, and two, they seem to range over all possible histories of the particles coming from the source.

In the double slit experiment, "each detected photon *could* have gotten to the detector by the left route or by going via the right route. Thus we are obliged to combine these two possible histories in determining the probability that a photon will hit the screen at one particular point" (Greene, p.181). Thus, the particles behave either as if the possible paths (and their different potentials) all mattered and influenced the chosen path or as if they travelled as a wave but interacted as a particle (Lange, p.286). This averaging of history, while present even in everyday macroscopic objects, is most obvious in the quantum realm and can contribute to a reinterpretation of classical presumptions like stability in time, object identity, locality and property possession in quantum mechanical terms. We do not know exactly how the particle-wave behaves beyond our invasive measurements, but its concluding interaction (absorption on the screen) indicates a much more complex relationship with space then was traditionally conceived.

For instance, in the double slit experiment we note that "the results of the experiment depend on the nature of the whole experimental setup, apparatus plus light (or electrons), and not just on the nature of light itself" (Davies and Gribbin, p.212). Our intuition is not equipped to make these sorts of predictions for the macroscopic world—for instance, no one supposes that whether we look or not means an animal will be a fish or a zebra—and the intuition is no clearer when considering the 'delayed-choice' experiments advanced by John Wheeler. He argued, and subsequent experiments demonstrated, that whether a photon (or electron) manifests the property of *behaving as a wave* or the property *behaving as a particle* can be determined *after* the experiment is complete. That is, if one decides not to look from the absorbing screen, one will allow the interference pattern to accumulate as in normal experiments where there is no detector positioned at the slit. But if one were to look at the experiment from the image screen, one could see which slit the particle passed through. Thus, it seems that whether or not the experimenter looks "back *at the time the particles arrive at the screen* determines whether or not the light *was* behaving in the manner of particles or waves at an earlier moment" (Davies and Gribbin, p.213). This is not just nonlocality in space, but in spacetime as well.

These three iconic experiments reveal some of the most challenging aspects of quantum theory in regards to the interaction of object and space, discouraging assumptions that space uniformly separates or that causation is local. Peering into the nature of space as a 'real, physical entity' as well as its potentially more dynamic moments (as vacuum fluctuations or expansion etc.) has left the possibility open for a more interactive monistic view of objects and space to develop. However, the construction of such a view should really come only after establishing a clearer conception of what space amounts to—and of how our expectations of separability are to be understood in light of modern physics.

8.4 Separability and Non-separability

These experiments suggest a blurring between space and object, which threatens our traditional assumptions about the role of space and the expectation that spatial distance *separates* objects. This concern is perhaps most pressing for the substantivalist since she deals with material *and* spatial substance, although related questions of object identity and distance relations will need to be addressed in some form by rival theories. Relationalists can choose to reject traditional notions of space, and either populate the universe with minute objects composing ever larger composites, or they may choose to find some other account of distance relations. Supersubstantivalists already identify material objects with their spacetime points/regions (so space is no special separating entity) and so may, say, attribute seemingly 'scattered' objects to law-bound property instantiations or some other constraint.

Nonseparability challenges one of the fundamental roles we invest space with—along with dimensional structure—and I want to put that role, and its competition, into context. With the physics of entanglement and quantum tunnelling (etc.) in mind, I will first review what we mean by 'separability', looking at some of the mereological options for separation and non-separability; second, I will re-evaluate our expectation for the uniform permeability of spacetime to objects including our rejection of co-location.

8.4.1 What Separability means

Separability is closely connected to locality, and both were assumed in classical physics such that phenomena were thought to be "completely described by local assignments of magnitudes" (Healey 2009). Historically, nonseparability has had a long-standing currency in the quantum community, and experienced something of a renewal with Schaffer's engagement with monism (Schaffer 2008). Niels Bohr's well known approach to quantum 'phenomena' encouraged an account in which observers (and perhaps a good deal else) were part of the quantum system. For Bohr, it is "a mistake to consider a quantum object to be an independently existing component part of the apparatus-object" (Healey 2009). Current physics' approaches to understanding phenomena favour a less-local range of assignments that include everything from nearby areas of *spacetime* points, to relatively distant physical processes. Separation thus implies, among other things, that if there are two distant objects (i.e. that have a measurable amount of space, occupied or not, between them in all directions), then an influence on one object will have no immediate effect on the other. That is: spatially separated states have independent real states.

Generally, nonseparbility is motivated by otherwise inexplicable statistical correlation patterns. There are arguments for it deriving from probabilities in quantum field theory and quantum mechanics in general, such that individual probability sets need to be integrated to obtain meaningful results (Placek 2004). In such cases it is the *system* that is taken as basic and primary for probabilistic calculations. Echoing the physics of Part I, we find that "the main new quantum properties of matter follow not from the use of the probability theory, but rather from the qualitatively new features of the quantum potential which, for example, imply a novel quantum wholeness such that the behavior of a particle may depend crucially on distant features of the environment" (Bohm and Hiley, p.42). Part of the reason for treating the quantum phenomenon as a system is its explanatory cohesion. For instance, if we took a "two billiard ball system as a single object, there would appear to be a mysterious constraint on the evolution over time of that object's energy distribution. That constraint can be made less mysterious by postulating the existence of billiard balls…There is no analogous explanation to be given of what happens in collapse in terms of finer parts of the superposed particle" (Parsons, 2003, p.13).

System 'states' rather than objects are the more common description of the quantum world, but even state[72] separability is insecure. Roughly, such separability assumes that "the state assigned to a compound physical system at any time is supervenient on the states then assigned to its component subsystems" (Healey 2009). All that is required for such separability to fail is for the subsystems to be either without assigned states or with states that do not fully determine the compound system's state. Given strict definitions of subsystems, modern physics' use of algebraic limits makes the failure of state separability (and the presence of nonseparability) surprisingly easy to achieve. For instance, even familiar phenomena like the electromagnetic field need not be separable as its value is determined by taking the limits over successively smaller *neighbourhoods* of points that spatially extend

[72] In quantum theory, the state of a system "gives a specification of its probabilistic dispositions to display various properties on measurement" and may play a role in specifying the state's categorical properties (Healey 2009).

further and further away rather than over the subsystems themselves. That is, values for the subsystem can be integrated with regions beyond the compound system's parameters.

Part of the problem may be the ontological interpretation attached to the mathematics in cases of separability. For instance, Belousek argues that an instrumental approach removes the strangeness associated with nonseparable states, which arises only if "the quantum state be interpreted ontologically, as opposed to instrumentally, that is, as representing in some (perhaps incomplete) way the physical reality of quantum-mechanical systems and not merely as a mathematical tool for statistical prediction" (Belousek, 2003, p.794-5). There is also concern from (Dickson 1998) and others that ontological holism is indicative of our ignorance of quantum phenomena rather than posing a viable scientific theory, and certainly it would require an overhaul of our working definition of events[73]. The interpretive caveat and concerns over ignorance are well-placed, but it is hard to see how we are to avoid ontological interpretations entirely, and *both* Bohmian and orthodox approaches thus far agree on non-separability and non-locality.

Locality, relatedly, assumes that the effects of an interaction are confined to the immediate spatiotemporal surroundings, and then causally transferred in a continuous way. Locality seems to encourage separation—by restricting effects in space—while separability seems to encourage local causal connections. At base, belief in separation means a belief that space separates objects; it is a belief that objects can be distinct from their surroundings and treated as separate in experiments isolating a particular quality. Locality focuses on action rather than objects, and belief in locality means a belief in local causal chains of action—in spatiotemporally physical laws having local causes. In Peter Gibbins' words, "locality means, among other things, 'no-action-at-a-distance'. It means that the properties of a physical system are affected only by events in the immediate vicinity. It also means that complex systems may be described as collections of interacting, but otherwise independent, components" (Gibbins, p.116). Separation and locality are thus intimately related, but it may be that conceding the loss of the latter makes us more open to exploring the former.

Although there are difficulties with both nonseparability and non-locality, it seems that physicists are embracing nonseparability. It represents a smaller modification to their

[73] Indeed, there have been suggestions (Vijay et al. 2012) that various quantum mysteries can be overcome through ingenious new experiments that somehow sidestep measurement barriers, but even if that is the case the nonseparable option deserves to be explored.

explanatory system given that non-locality already accompanies their theories. For if we lose locality, we seem at a loss for figuring causality and prediction in general; we could lose the heart of scientific practice. Finding some way to keep it, on the other hand, may open our ontology to strange objects, but we are getting rather used to that by now. Nonseparability—if it is to be distinguished from non-locality at all—may represent nothing more than a new type of object—a multiply located body or force that is not isolated by intervening spacetime regions. Non-locality, on the other hand, looks as if there are new or different *laws*, which poses a far larger revisionary problem for the explanatory system, and must be modified in such a way as to preserve the successful local accounts given to the majority of other scientific disciplines. Furthermore, non-locality drags—at least a type of—nonseparability with it, in that instantaneous spooky action at a distance would erode our belief in separate objects that can be experimented upon in some form of isolation.

For instance, under such an interpretation, the modification of behaviour witnessed in interactions like the Aharonov-Bohm (AB) effect which appears distinctly nonlocal (where electrons behave as if they were experiencing a magnetic field with which they are never in contact), may be recast in a holistic framework as the *local* action of nonseparable electromagnetism. The most common way of representing this is by taking the electromagnetic field as a "set of intrinsic properties of loops in…space-time…[which] do not supervene on any assignment of qualitative intrinsic physical properties at spacetime points in the region concerned, nor even in arbitrarily small neighbourhoods of those points" (Healey 2009). Nonseparability compellingly accounts for the AB effect, as the interference pattern produced by the particles *indicates* the spatially absent electromagnetic field.

If nonseparability is indeed more appealing to physics, then the philosophical accounts of more exotic objects may have a very functional role in distancing science from non-locality. Currently, however, and since Bell's inequalities were published, much of the discussion has centred around non-locality (e.g. Maudlin 2002), with some vague hope that a unification between relativity and quantum theory will explain away the issue. Non-locality, at least given our general physical account of the world, leaves a particularly large set of unanswered questions that have the structural significance (in our explanatory system) of accounting for a set of interactions between fundamental particles. That is, non-locality requires an important addition and/or modification to the fundamental laws (or dimensional structure of space); nonseparability *could* mean a change to physical laws, or it might just mean a new type of object—and this latter interpretation may be easier to account for given the rest of the explanatory system.

For metaphysicians, nonseparability still produces problems for accounts of objects (as we have seen), properties and causation, even if these problems are often ignored. If descriptions of an object or process need to extend beyond the traditionally assigned prima facie boundaries, then we ought to explore in what way they extend—for instance, is it continuously or discretely? Is it across gunky regions or atomic bits? In what way are objects separated from each other and how are they separated from spacetime? A piece of the conceptual answer should include an account of how objects (in whatever form they are conceived) negotiate their surroundings, and whether space uniformly interacts with objects as classically conceived.

8.4.2 Spacetime Permeability

Given that one of the things we expect spacetime to do is to separate objects, we may wonder whether this separation is or ought to be uniform; that is, whether sets of particular masses or other properties traverse spacetime for the same duration per distance travelled. Do we have good reasons for rejecting the heterogeneous permeability of spacetime? Might some objects traverse it, penetrate it or otherwise interact with it in a non-uniform manner such that it could explain observed phenomena? One could argue that through certain quantum phenomena (such as quantum tunnelling), physics has encountered reasons to make us entertain this possibility and to offer an account of how this might happen. So, perhaps instead of searching for some hidden variables to explain quantum nonlocal correspondences we might contemplate a new class of nonlocal causes through a new appreciation for how space *behaves*. For example, space may be selectively permeable where once we thought it presented a uniform path for all objects. That is, we could swap new laws of spatial heterogeneity for the unsettling quantum nonlocality.

One way we might account for perceived non-uniform permeability may be through a dimensional perspective by the routes traversed through spacetime. It is conceptually possible for different objects to interact with spacetime in different ways, following snaking line paths at some times and bridging paths at other times, and I can see no reason why all objects *must* interact in a uniform and consistent manner with spacetime. Metaphysicians such as Hudson, seem happy to consider a variety of more exotic objects that might address this since there seems to be no proof of their impossibility; some objects may have a relation of 'multiple location' to a plurality of spacetime regions while other objects have only a relation of 'single location' to one spacetime region. Perhaps these different sorts of objects and/or interactions are just what we need to explain some of the more bizarre physics.

Part of the tacit assumption in our search for determining the *means* of separation and distance, is that it contributes to distinct objects—objects that are isolated from other objects in the region they exactly occupy. That is, the separation of objects is important to prevent co-location, something commonly avoided—as we saw with (Schaffer 2009) in chapter 5. But what is it that motivates this view that objects are separate in this way or immune to co-location, and is it necessary for our metaphysics? It is hard to see how we could accept co-location, but even if we maintain the ban on it we should be very clear why it is there, especially when so many of our intuitions about objects become problematic. It may be that we are over-eager to follow our intuitions and traditional beliefs about what it is to be an object, such that we give objects more structure than that for which physics accounts. That is, spatial points may not be 'monogamous' with one material occupant, able to interact with more than one object simultaneously. The reasons we have for rejecting this view seem to stem from its unintelligibility given our experience; for example, it seems impossible for something to be two different colours all over; it does not seem possible that an object is spatiotemporally all blue and all red.

But we are generally happy to concede that objects and events can co-locate, or objects and property instantiations, but perhaps we are overly biased against other phenomena co-locating. There are already unintuitive processes that can be seen to encourage a more inclusive approach; for instance, in some sense waves and particles are co-located, and the elusive nature of mass-energy equivalence in general. At the very least it is something to bear in mind: when we are presented with seeming co-location we should not reject it offhand, but seek a different perspective, and perhaps a more holistic one. If spatial interaction is not homogenous and spatial separation does not guarantee causal separation as classically conceived, then we should wonder what it does guarantee, and whether space is anything more than a conceptual but unreal tool. The remaining chapters examine such additional characterisations of space with a focus on its supposed dimensional structure.

CHAPTER 9: Space; the Convention of Fact or Fiction?

There are some that think space to be a real something, agreeing with Nerlich that “space is a particular with a definite structure, a topological one, just any other particular thing…it is a real live thing” (Nerlich, p.194). And others who argue that such structure is derived from the matter ‘within’ it, that “space is in the first place a device introduced to describe the positions and movements of particles. Space is therefore literally just a storage space for information. This information is naturally associated with matter” (Verlinde, p.6). Of course, space may *be* the information, or at least a vital part of it, and we may perhaps be wary of concluding that it is space rather than some other property that separates objects. Space can certainly keep bodies apart, but arguably “by way of giving a logical condition, not a causal one: space is needed if we are to be able to speak of objects as being apart, but it is not the instrument of their separation” (Rundle, p.219). This last stipulation is of course controversial, but relationalists and those that entertain multiply-located objects may embrace it (and given the physics related in Part I). This important logical role for physical space has encouraged us to develop other coherent and complex abstract spaces, which reflect selective perceived relations between objects or pieces of information.

This distinction between physical space and abstract space is interesting, not least because of which qualities it reveals as the grounds for our metaphysics. We find things like momentum and geometric position on an extended coordinate system to be valuable for explanation, prediction and organisation in a way that we do not find sensory qualities like colour, smell or mood[74]. But we can talk of *abstract* momentum or position in *abstract* spaces in mathematical texts or when making weather charts or financial analysis reports. In this we can separate the concept of space from physical space, though the details and rationale for this separation may be somewhat lacking. As noted above, space is instrumentally useful for revealing objects, but it also actively participates in the behaviour and characteristics of those objects and is interesting in its on right.

For these reasons, it matters whether we are realist about space or not. So beyond looking at problematic issue of spatial separation, I here explore if we can distil what ‘physical space’ is in a realist sense, and to help motivate the analysis by looking at some of the physics that challenges traditional conceptions of space. I conclude that, among other

[74] Physical space need not be limited to what we can perceive, since at least conceptually there could be many things that are physically real, in an important sense, that evolution never required homo sapiens to perceive.

attributes, physical space is characterised by its epistemic value to us and by its sensitivity to all measurable change that bears the possibility of interaction with the material of our world.

9.1 Abstract Spaces

When we refer to ‘space’ it is not always clear what we mean; there are many kinds of spaces, from the space between my hands, to outer space, to economic space and measured space. We invest our time and formalism in these spaces because they all serve an explanatory role; they explain future behaviour, how certain properties relate, or why things are separate. However, I am interested in what properties can be attributed to our physical space—the space that we all move through/in/by—and part of figuring that out involves separating it from other spaces. What is it about certain spaces that makes them abstract[75] and non-physical? Given the prevalence of space in our discourse and theories, we should expect a ready arsenal of properties we can use to flesh out the concept of space; but, as we saw in chapter 8, such stalwarts as ‘definite place holder’ and ‘means of causal separation’ are challenged by phenomena that blur the boundaries of object and space, and that appear to permeate or transcend spatial distance. Physicists routinely deal with super, configuration, phase, spin, superposition and isospin space, all of which examine relations between objects and their properties—especially via mathematical symmetry operations—but as usual there is some uncertainty about whether or why such spaces are abstract. I will very briefly survey each of these in an attempt to review some of the criteria for physical space and reveal the uncertainty surrounding it.

[1] Superspace

Superspace is a space in which impressive unification seems possible—again, much like the electric and magnetic forces were recast into the one electromagnetic force—taking certain types of mathematical operations to reveal important differences in the manifestation of something that in some way is fundamentally preserved. In this, it is founded on mathematical symmetry, which is among the most central principles in physics, guiding mathematical exploration, theory formation and prediction. Symmetry also has the benefit of simplifying calculations and reducing several degrees of freedom to a single element (Siegel, p.38). Not only does symmetry feature in our best theories of everything, it also appears in

[75] Although certain quotes may appear to pit 'abstract' against 'real', I mean to contrast the former only with 'physical' and leave the dispute about the reality of abstract entities to others.

all interactions between fundamental particles in the form of gauge symmetry for local transformations. Roughly,

> A symmetry is a transformation (a change of variables) under which the laws of nature do not change. It places strong restrictions on what kinds of objects can exist, and how they can interact. When dynamics are described by an action principle (Lagrangian, Hamiltonian, etc.)…continuous symmetries are equivalent to conservation laws, which are the sole content of Newton's laws (Siegel, p.38).

The similarities in behaviour or properties between fundamental particles has led the physics community to regard many such particles as possessing a unifying symmetry, which both dictates the types of interactions and particles available, and explains the observed 'families' of particles and interactions. More ambitious unifying theories have developed a (yet unproven) supersymmetric theory that links quite disparate members of the particle family in complex ways that may or may not be a reflection of a physical unification.

For instance, supersymmetry theory assumes that the masses of fermionic and bosonic particles are intimately related to each other, with particles from each group partnered with opposing superpartner fields (which are thought to have gone unobserved because they only appear at abnormally high energies). That is, bosons of spin 1 (e.g. gluon) are paired with lepton and quark superfields of spin 1/2; and the boson of spin 2 (graviton) is paired with a superfield of spin 3/2. But "supersymmetry doesn't just pair up bosons and fermions, it also enlarges the notion of space-time to pair up ordinary coordinates with fermionic coordinates" (McMahon, p.169). This creates a superspace of superfields that incorporates both the normal 4 bosonic dimensional coordinates and additional four fermionic dimensional components. These coordinates form the dimensional parameters of an *abstract* 'superspace' that nonetheless strongly resembles physical space in its content and description.

Relating observed particles in this way not only simplifies and smoothes the mathematics by removing infinities, it also provides a more fundamental explanation for the structure and type of particles in our best account of particle physics. The diversity of particle types is explained by the movement of one basic object, the string, just as the diversity of musical notes can issue from a single plucked string. To capture this intimate and reductive connection between particles, several spaces are conjectured: "In the superspace, we can think of bosons and fermions as two different projections of a single object, much as an electron and its neutrino can be thought of as two different projections of an object in an internal space" (Kane, p.67). If we can think of two seemingly different objects as one in the superspace, can we also think of them as one object in *real* physical space? That is, "does the fact that (before symmetry breaking) a boson can be transformed into a fermion by the supersymmetry transformations mean that the two are, at a deeper level, a single particle…Or does it just mean that physically the two can change into each other?...The answer appears to hinge on how realistically we can (or should) interpret superspace" (Weingard, p.147).

The total lack of empirical verification of this hypothesis generally keeps physicists guarded about the reality of superspace. So although this sort of interpretation is tempting, the additional coordinates are not thought to be dimensions of *real* physical space, rather, they are a "purely theoretical device" (Randall, p.262). But what is it about them that is not (physically) real? We might suggest that there are three main reasons for calling it a non-physical *space*, that is, 1) the directions are ones we do not observe, i.e. there might be nothing beyond mathematical formulae—and nothing we could in principle construct—to access them, 2) the properties are ones with which we are unfamiliar, e.g. not having a determinate value, and 3) it looks suspiciously like mathematical gymnastics in that we may not be able to match the mathematical terms to known phenomena. We still call it a space because we find it *useful* to posit it anyway. Superspace, then, like many other abstract spaces, gives a place for certain properties to be related, often benefiting from geometrical relations, functions or spatial structure.

[2] Configuration and Phase Space

Configuration and phase space also follow this model by offering a place to compare *all* the physically possible states of a system and what that would mean over time. Such an expansive space is useful given the general assumption in quantum mechanics that whatever can happen will happen, barring certain brute constraints, such that mapping out statistical averages over such a space can give better behavioural predictions. Part of the rationale for this doctrine is the observation of certain phenomena (e.g. the firing of electrons through slits at screens) that behave as if they had taken all possible routes or 'histories' from one place to another. Such behaviour has led to the creation of a 'configuration' space "which is taken to be the space of possible configurations of some set of particles or fields relative to physical space" (Belot and Earman, p.216). In this case, and in such areas as statistical mechanics, such a system's microstate can be specified by a scalar number that is considered a degree of freedom. The collection of possible states for one or many particles or fields are calculated in terms of a manifold (hence the configuration manifold) and offers a useful tool for calculating probabilities.

Expanding upon this, mechanical systems take the cotangent bundle[76] of the configuration manifold to account for both position *and* momentum; that is, the specification of all microstates of a system can be a point in a larger manifold called the 'phase space' of the system. Phase space takes every parameter of the system to be a degree of freedom with its own dimension (and thus axis), such that a particle's position coordinates and momenta among other properties would each require separate dimensions. Phase space can thus be a useful means of charting the *evolution* of possible and probable states over time by relating the possible *relevant* variables in a timeless way (e.g. on a graph). Reducing a variable's possible states to one element is something that does not seem possible in our real space, importantly because time appears to us as such a dynamic *unfolding* dimension that the thought of collapsing it into other values for a single 'location' in phase space is counterintuitive. However, given the scepticism with which many scientists view pre-theoretical intuitions, this hesitation may not mean much—in fact, such spaces may highlight a more fundamental explanation of the nature of space.

[3] Superposition

Another abstract space that mathematically reduces important physical variables is associated with superpositions, where 'position' here is much more about the probabilistic position potential for a particle or qubit (smallest non-trivial quantum system) rather than a multiply-located or higher-dimensional position. A qubit is the superposition of probability amplitudes, or states, and its "0 and 1 values are represented by quantum states that can be reliably distinguished – for example, horizontal and vertical polarizations – but coexisting with these are the whole continuum of intermediate states such as diagonal polarisations that lean toward 0 or 1 with different probabilities" (Gleick, 2011, p.365). That is, the value is physically indeterminate for a given observable. One way to make sense of this is by supposing that either real space somehow allows all these positions to actually be held, or there is a function that ranges over different universes where all the position values are actualised until an interaction collapses it.

[76] The cotangent bundle gives the spaces around every point in the manifold, such that when mapping out the phase space of a circle, the resulting space looks like a cylinder.

One might establish a superposition of a lump of material “where each individual state has a well-defined static mass distribution, but where the mass distributions differ from one state to the other…In the absence of any spatial inhomogeneity in the background potentials…there is nothing in the intrinsic nature of one lump location that allows us to distinguish it from any other lump location” (Penrose, p.293). Quantum general relativity, such as it is, follows Leibniz in assuming that the lack of physical difference implies that all lump states are the same. In quantum mechanics, however, the differences are preserved in order to assign all the calculated wave functions for the lump (particle) in the form of superpositions. Such a way of being ‘located’ is something we never experience in the macroscopic world, and struggle to makes sense of in physical space.

It is unclear whether we ought to interpret this as fundamental indeterminacy (resulting from ‘a lack’ of interaction), or as an indication of the Many Worlds approach to quantum mechanics that allows for each of the possible values to be observed in *different* universes. That is, in measuring the polarisation of an electron, say, there is a *space* where each possible value from 0 to 1 *is* recorded (just not all in the same space). Many are reticent to interpret this in the realist tradition and instead view the account in purely instrumentalist terms, whereby our ontological theorising is limited to making predictions. Being very clear on why superposition cannot or *should* not conceptually be part of physical space will be important in articulating what physical space is, even if we cannot yet empirically verify the physics involved.

[4] Spin space

In addition to superpositions and the abstract space they invoke, elementary particles can have both orbital and intrinsic spin (or ‘intrinsic angular momentum’), which is thought to be somewhat analogous to the earth spinning around the sun and around its own axis, respectively. This latter type of spin is not strictly analogous however, as the space in which many particles with spin turn requires more than one 360^0 rotation to return it to the original state. For instance, fermions seem to require two full turns to return to an original state, which perhaps reveals some unseen topology, where “one full turn produces a state topologically distinct from the original state but two full turns produce a state topologically equivalent to the initial one” (Gardner, p.331).

This exotic property may derive from a yet unknown property of the particles (e.g. twisting as it ‘turns’ such that two 360^0 revolutions are needed to restore the original symmetries) rather than from the demands of a higher dimensional space, or perhaps some other restricting feature of our universe. But beyond this curious spin, such particles are also credited with another, more abstract, spin called quantum isobaric spin, or isospin (Schumm, p.187), whereby different particles that engage with the strong interaction (say a neutron and a proton) can be considered the same particle through the invocation of an "abstract inner space called *isospace*" (Gardner, p.327). In this space a neutron can be 'rotated' into a proton by altering or rotating one of the constituent down quarks into an up quark.

Particles like the neutron and proton are composed of certain types of quarks (up and down) that produce such similar strong force interactions that they are thought by some to be different states of the same particle, perhaps not unlike the two sides of the same coin. It seems that either they are the same particle in our physical space, or that they share an important underlying property. It may be a matter of deciding what characteristics need to be preserved for identity ascriptions in order to better gauge whether the two particles should *be thought of* as the same particle or in what way we can claim that they *are* the same particle. For instance, a 2 year-old me and an 80 year-old me are in some ways fundamentally the same being, even though the behaviour, mass and perhaps every single atom are different. It may be that utility will drive whether we view neutrons and protons as essentially the same, although for now the abstractness of the space dominates. Many physicists like Barry Schumm think isospin rotations "are mathematical edifices, spaces with no more physical content than the space in which I plot my checking account balance against the unyielding advance of time" (Schumm, p.204).

This space is useful for manipulating values and charting the evolution of relevant variables over time or in relation to other like elements, but there remains something decidedly unphysical about such a space, with physicists interpreting "isospin-space as an internal symmetry space, while asking 'but what is that, really?'" (Schumm, p.194). As with the other spaces, should such 'flavour' symmetry operations unify the particles, then I suspect we would interpret physical space as we know it to expand in complexity to encompass such relations largely because it is in physical space that we ground—and keep a record of—concrete entities. That is, I do not think there is anything preventing space from permitting such operations, especially if the operation amounts to no more than a shift in perspective akin to describing phenomena on the one hand as a gas with temperature, or as a number of molecules in motion on the other. The other spaces mentioned, on the other hand, seem to offer only a certain reductive *way to perceive* the features of reality (e.g. particles, speed, position), and thus a narrowing of the totality of information offered by physical space (even phase space is a reduction of the information available to chart certain information over time). Thus, they are more akin to places for comparing ideas and, like geometry, create a representation of physical reality in human-friendly measuring spaces (e.g. representing the earth on a rectangular map).

We might claim, then, that we call a space 'physical' for both epistemological and constitutive reasons. Epistemological because of the fundamental structuring (one of the Kantian conditions of physical experience) and explanatory role space serves, and constitutive because certain concrete elements exist and together occupy, or create, a physical space. As noted in the introduction to this chapter, we rely on space to explain various aspects of our experience, providing an important conceptual framework for many of our ordering and predicting endeavours. Traditionally, as is likely still the case, we call things physically real because we can or could interact with them.

Abstract spaces, on the other hand, give us ways to mathematically represent and geometrically plot relations and predictions for aspects of entities in telling ways that move beyond their limitations in physical space. For instance, we can formulate a space where all the objects in a room are situated by their position on the colour wheel rather than their physical position. While important in their own right, such abstract spaces do not give us a clear definition of space in itself, though they may highlight some of the characteristics we attribute to physical space, which can be described in terms of a) 'states' where each change in information value (e.g. each qubit of information) and all manifestations of matter and energy are registered, and b) as existing along a continuous coordinate system of material units in which we are located (giving us the possibility, in some sense, of interacting with it[77]).

While these characteristics may not definitively and exclusively describe physical space, they do seem important characteristics and the ways we define abstract spaces have raised the importance of both information and fundamental units that can be geometrically expressed to a conception of space. Choosing which fundamental units determine the space, however, is unclear, although in regards to abstract space, it is not obvious that one can go from an abstract space to our physical space without the addition of more information; that is,

[77] Our way of 'interacting' with the number line or a checking balance could certainly be examined in detail—to see if it merits the same terminology—although I doubt it.

though we seem comfortable isolating elements from physical space in order to formulate abstract ones it appears easier to move *from* physical space to abstract ones rather than trying to reconstruct all the information in physical space from an abstract space. In general, I think that the distinction between physical, in some sense concrete, and abstract space needs to be clarified, particularly as there are so many unclear examples in physics that need stronger guidelines for their classification in this regard. Nonetheless, these characteristics do not demand that physical space be either a unique substance or even a physical entity. That is, physical space need not be a *substance* to be distinguished from abstract space. Space may be nothing more than our term for the collective organisation of matter, and nothing at all like the robust creature of substantival models.

While physical space need not be so very fundamental, it does need to have some sort of structure to characterise it, and ideally to afford the kinds of distinctions we expect (e.g. determining whether an object can be enantiomorphic). This belief, along with the mathematical demands of the energy values for such fundamental units as charge, momentum, spin etc., naturally leads to talk of dimensions—the seemingly immaterial structuring of all interactions that determines whether, say, a 'left-facing right triangle' can be manipulated into a 'right-facing right triangle'. Dimensionality can certainly populate abstract spaces—indeed, it was variously manipulated in all the above cases—but it is a characteristic that has long been thought to belong to our physical space. Our three-dimensional construction of space and then four-dimensional construction of spacetime has proven wonderfully fruitful for engineering and mathematics, and traditionally constitutes an important part of our understanding of space. Having struggled to 'discover' the nature of space in the substantivalist's point-based manifold and in comparisons with dubiously abstract spaces, it is tempting to suppose greater insight will accompany the supposed spatial structure of dimensions—which will occupy the remainder of this work—if, that is, we can figure out what they are.

CHAPTER 10: What are Dimensions?

Rather than promote a given philosophical position at the expense of another, as I do in other chapters, in these three chapters I want to raise a subject for debate, namely, the concept of a dimension which, despite its common and broad usage, is not clearly defined and more alarmingly, the philosophical community does not seem to recognise this as a problem. I think this does a disservice to both philosophers and scientists, and produces a confused and fractured account of some of our best theories of the world. My aim here, therefore, is principally to illustrate both the importance of the term and the need for much more work on it to be done. In this, I will be highlighting areas I find particularly fruitful and asking more questions than giving answers, with modest hopes of a spring cleaning for the concept rather than a rigorous and complete account of dimensionality.

Whether attributed to spacetime or to objects, the property of 'dimension' has played an increasingly significant scientific role over the last century, leading to its current usage as a crucial contributor to our fundamental theories (whether superstring, supergravity etc.), and thus as much as the notion of a 'field' or a 'number', it deserves our attention. This prominence of spatial dimensionality as a physical tool began with mathematicians in the 19th century[78] and then in earnest in the wake of Einstein's special theory of relativity. From there, a series of developments in dimensional discourse—from the four dimensions of Minkowski spacetime and the suggestions of Kaluza-Klein theory, to the mathematical cohesion of superstring theory—expanded the range and kind of theories considered by physicists. The first waves of inquiry into extended dimensions have given way to the mainstream, and there now seem to be very few physicists who do not seriously consider 4+ dimensions constituting our reality.

However, this ontological proliferation has received scant attention from philosophers and only cursory attempts at elaboration by scientists that often mention it in terms of degrees of freedom. Dimensions are nearly always defined via simplistic examples that focus on lower spatial analogues and often frustratingly end in 'etc.' as if the unobserved were obvious. For instance, a point is zero-dimensional because it allows no movement along any direction and there is no uncertainty about the location of anything 'on' that point (because there is only the point). A line is one-dimensional because it allows movement along one

[78] A few earlier mathematicians like D'Alembert and Lagrange took mechanical geometry in four dimensions more seriously, even suggesting that time is a fourth dimension, but this could not be called prominent.

direction (say, left/right), and spatially locating anything on it only requires one piece of information. A Euclidean plane is two-dimensional because it allows movement along two directions which are orthogonal to each other (say, left/right and forward/backward), and because two pieces of information are needed to spatially locate an object on the plane. The rationale for incorporating orthogonality into the definition of dimension follows from our use of independent variables along standard 90^0 coordinate axes, as in Leibniz's definition of dimension: "the maximum number of mutually perpendicular lines that can be drawn through a point" (Dipert, p.63).

Polar coordinates also require two pieces of information, though one is an angle and one a length from the origin. Our visible world is three-dimensional because it allows movement along three orthogonal directions (say, left/right, forward/backward and up/down), and requires three pieces of information to spatially locate an object. Following this, we are generally informed that 4, 5, 6 etc. dimensions follow this pattern, with a temporal dimension tacked on for good measure. In all of these discussions of dimensions as determined by the number of information pieces used to locate an object, there is the rather large additional and uncounted inclusion of a coordinate system with a proscribed centre, as well as the understanding that this whole contraption models some aspect(s) of the universe (e.g. classical observables, mass etc.). That is, there is a fair bit of framework that supports the dimensional house of cards, which may be influencing more than we realise and certainly could lay claim to being an additional piece of information, though I am not sure what exactly to make of this.

The familiar three *spatial* dimensions above have been the endorsed number for hundreds of years, with philosophers like Aristotle and Kant[79] offering brief discussions on the topic that invariably amounted to little more than a by-the-by statement of fact[80]. Their views are no longer taken for granted, however, and philosophers who continue in that line of argument need to give more compelling arguments than, say, Richard Swinburne's push for tri-dimensionality, whereby he seems to equate 'logical' with 'readily sensible', appealing to one's intuition (through several examples) to show the difficulty in conceiving of our world being greater than three-dimensional (Swinburne, p.152-4). This of course hardly amounts to

[79] Descartes, as will be discussed later, was a notable exception, although his application of the term 'dimension' to any measurable quantity is different than what I have in mind here.
[80] Although philosophers may attempt to corroborate or explain our world's tri-dimensional appearance, they cannot go beyond the evidence, and "all our empirical arguments for the dimensionality of spacetime prove only the importance of 3 + 1 space-time throughout its intimate interconnection with our most general physical laws. They do not and cannot show that there is anything intrinsically necessary about this structure" (Graves, p.200).

any kind of a substantial proof for the impossibility of our world being so constituted. The difficulty one has in conceiving of infinite expanses or of an electron cannot be taken to refute the existence of either. More recently, time has been cast as an additional dimension, an add-on to whatever number of spatial dimensions one likes, though it has hardly escaped anyone's notice that a temporal dimension is not the same species as a spatial one.

While this particular difference *has* received more philosophical notice, the dialogue has not, by and large, focused on dimensionality per se, but rather on concepts like the nature of temporal existence, mereology or change. One might think that at least with the proliferation of spatial dimensions there would arise a more rigorous analysis of what we expect of a dimension, how we use it, and what, exactly, a dimension *is*. But the physical analysis has not kept pace with the mathematical, and it is easy to stumble upon confused or unsure physicists or even mathematicians that only discuss the *differences* between dimensions (e.g. in topology or shape), and wonder what exactly they are referencing, as the next section notes. Our failure to flesh out the definition may rely to some extent on empirical data, but there is certainly ample room for a more profound and elucidating account of dimensionality as it is currently used and understood in physics[81]. I will first review some of the explicit confusion concerning dimensions, and then explore the central topics such an account should include.

10.1 Underdetermination, Confusion and Equivalences

Dimensions, like fields, or particles, or space, are important because they are thought to underpin and inform our understanding of the universe. Whether dimensions (or any of the other listed concepts) are physically real or merely instrumentally useful matters; it makes all the difference whether, say, one's mother or car or imaginary friend is physically real *or* only an instrumentally useful abstraction, like the 'average family'. Is a dimension the sort of thing that affects physical processes with different numbers of dimensions giving rise to the same physical phenomena? Is dimensionality even a property of space or is it wholly or partly a property of objects? We appeal to dimensions as fundamental structures of space and even as the shapers of properties themselves, but without a clear account of what we mean by the term, significant empirical data will have no framework to fall into, neither confirming nor disconfirming the vague definition of dimension *some* of us *at times* hold.

[81] The colloquial use of 'dimension' in terms of personality, society etc. is set aside in the current analysis.

It is not simply a question of asking the physicists what they use dimensions for, because there is no unified or thorough response to be had. Mathematicians can be even worse, since they seem to happily proliferate dimensions as their calculations require, leading to the comforting thought about the quantum field that “the multidimensional nature of this field need not then be so mysterious since information can be organised into as many sets of dimensions as may be needed” (Bohm and Hiley, p.61). Because of its slippery, even purposefully vague definition, ‘dimension’ is used to sort and describe a range of information and phenomena. To put this information to the best use, there needs to be an effort to consolidate and clarify, and at least question, the conceptually possible and practical roles of dimensionality.

The endeavour of analysis is a process begun by the physicists themselves. Harvard physicist Lisa Randall devotes a book—and much of her career—to an analysis of physical dimensions, but she closes the text questioning what she means by the term, particularly in regards to equivalent theories with disparate numbers of dimensions: “what does the number of dimensions really mean? We know that the number of dimensions is defined as the number of quantities that you need to locate a point in space. But…there’s a plasticity in the definition that eludes the conventional terminology....Because no single theory is always the best description, the question of the number of dimensions doesn’t always have a simple answer” (Randall, p.449).

In particular, we find theories exchanging seemingly quite disparate properties like momentum and charge, each meriting its own dimension: “the number of directions is the number of independent directions of momentum—that is, the number of different directions in which an object can travel. But if momentum along one of the dimensions can be replaced by a charge [and some theories claim it can], the number of dimensions isn’t really well defined” (Randall, p.320). This concern should be twofold, as there is uncertainty regarding both the number of dimensions science ought to embrace (perhaps based on evidence or utility or coherence with other models), and uncertainty regarding the nature of dimensions (are they physically real? Mathematically real? Instrumental?), which then affects what and how we count. It is this latter uncertainty in particular that makes discussing the number of dimensions such a non-starter; there is no piece of evidence that can settle the matter since scientists like Randall are not yet in agreement as to what they are looking for and what sort of evidence would confirm whatever that is.

She is not alone in her concern, Brian Greene echoes her uncertainty: "what can we mean by dimension when our mathematical theories that demand a number of dimensions of movement, are equivalent to other theories where the size, shape and number of dimensions can change?" (Greene, p.477). This uneasiness is largely brushed aside in the day to day work of physicists and mathematicians, but the growing reliance upon dimensions in their theories makes it increasingly difficult to ignore. Indeed, such distinguished physicists as the Nobel laureate Steven Weinberg have noted (if half-heartedly) that "we could use help from professional philosophers in understanding what it is that we are doing" (Weinberg, p.24). It is the greater wonder that philosophers have been so slow to respond to the invitation.

Perhaps the most important source of concern for physicists about dimensionality is the above referenced equivalence between theories. Our simplistic account of dimensions assures us that, if nothing else, different dimensions produce very different worlds; a 2-dimensional house is fundamentally different than a 3-dimensional house. It should be unsurprising, then, that physicists are unsettled to find that their theories of the world with different tallies of dimensional numbers appear equivalent in their description of physical phenomena. For instance, "there seems to be an equivalence between ten-dimensional superstring theory and eleven-dimensional supergravity" (Randall, p.304), as well as an equivalence between infinite (or approximating infinite) dimensions and very minute rolled-up dimensions (known as T-duality) [82].

This equivalence has the potential to unite what were once seen as two competing 'theories of everything'. In addition to such flexibility, dimensions have the power to unify or separate objects and phenomena in profound ways, not only making seemingly incongruous counterparts congruous counterparts via a higher dimensional flip, but unifying the force carriers (bosons) with the matter particles (fermions) and joining all the fundamental forces. For instance, although our visible spacetime presents electric and magnetic fields as similar, in other dimensional models they lose that symmetry and appear quite disparate (Yau, p.68).

This also applies to seemingly interchangeable theories that posit different numbers of dimensions but require the same number of values to uniquely identify a particle. Because this interchangeability has proven such a catalyst for questions about dimensionality, it

[82] The circle radius of a rolled up infinitely large dimension would yield no number, no circle at all, and a zero-size circle does not count as a dimension so it may be taken as equivalent with a theory of one dimension fewer (Randall, p.451).

behoves us to spend a moment on what sorts of equivalences physicists have in mind. The different versions of string theory display a topological T-duality symmetry that relates the large coupling strength (energy of the interactions) or small distance of one theory to the weak coupling strength and large distance of another theory to show "that the two theories are in fact the same theory expressed from different viewpoints" (McMahon, p.159). Thus, type IIA theory with its small compactified dimension with radius *r* and tightly wound strings is dual to type IIB theory with its huge dimension of radius *r** and directed momentum; "each time the string in type IIA theory winds around the compact dimension, this corresponds to increasing the momentum in type IIB theory by one unit" (McMahon, p.160).

There are further equivalences with this element of 'sameness' derives from the persistence of mathematical variables in the descriptive formulae, which is interpreted according to observable phenomena like momentum and charge. Mass can also be in some sense created through dimensional analysis "by 'dimensional reduction', identifying mass with the component of momentum in an extra dimension. As with the extra dimensions used for describing conformal symmetry, this extra dimension is just a mathematical construct used to give a simple derivation" (Siegel, p.141). Positing an additional spatial direction extends the range of available indices and allows the corresponding momentum to equal the mass, given renormalizing transformations (Siegel, p.142). The different perspectives achieved through various radii (in this case) are thought to describe the same objects; similarly, a description of motorway traffic could include the bundles of pistons, engine, wheels, shafts, seats etc. and how they interact with the road in complex high-energy ways across 4 dimensions, or it could include 'cars' and traffic flow patterns from a slightly different, simpler perspective.

There are additional mathematical approaches that study the evolution of dynamic systems and seem to give some sense of the interconnectivity associated with higher dimensions. This sense appears in more exotic models for phenomena, say, the description of a dynamical system's evolution wherein the points of the evolution curve remain close to an original 'attractor', which itself could be a point, manifold or a fractal structure. Here the evolving system is always closely connected with its origin *and* to other points; "this concept of dimension gives a measure of the amount of information necessary to specify the structure of the attractor" (Barrow, p.343). The interconnectivity of such structures may merit a multi-dimensional analysis of their information in a similar way to the highly complex behaviour of other objects and systems.

Although it provides no physical interpretation, this mathematical approach of shifting the 'view' to different dimensions is common. For instance, "using the tools of renormalisation and perturbation theory, rescaling phenomena to different spatial dimensions can shed more light on the behaviours involved; for instance… we can gain a better understanding of matter in 4D by looking at the field equations in 5D" (Wesson, p.21). Again, the rationale appears utility-based; we find it helpful and informative to explain events and properties under the assumption of different boundary constraints. Dimensions, however they are perceived, fulfil this role and offer an explanatory framework to make sense of information.

Dimensions can have more subtle interactions than unifying all particles by determining (or being determined by) the energetic strength of the entities involved. Strongly interacting theories seem to give rise to additional dimensions while the 'same' world at a lower energy might then be interpreted through a lower dimensional model (Randall, p.448). The technical difficulties of working with more energetic models have lead researchers to use a renormalisation process called perturbation theory to make the calculations tractable; that is, one can alter the perspective by describing a higher dimensional model in lower dimensional terms and choosing a different level of precision and scale (e.g. describing the motion of 3-D cars using only a 2-dimensional plane). Our move from speaking of 'a gas' and speaking of its constituent molecules is also similar, and although we may lose descriptive power at one level we may gain it in another through simplicity and applicability.

Dimensions can also link seemingly disparate theories; for example, in ten-dimensional superstring theory one needs to specify nine values of momentum *and* a value of charge (thus 10 values plus time), whereas in eleven-dimensional supergravity one needs only specify ten values of momentum (plus time). That dimensionality appears to embrace a range of phenomena (such as a dimension of charge) by reducing properties to a number of mathematical terms seems reminiscent of Descartes' approach to treat dimension as simply a 'measure of something', a way of organising information (see 10.2). The interchangeability of higher dimensions with lower dimensional values may suggest an instrumental interpretation or it may suggest an ancient confusion between one and many (e.g. a gas vs. many molecules). Or again, it may mean that, though there are real structures in place or facts of the matter about the number of dimensions, our interests and abilities prompt a fluidity of reference. Dimensions certainly have the potential for wide-ranging unification that could challenge a number of philosophical assumptions in the areas of ontology (e.g. are bosons and fermions really just one complex particle?), of universals (introducing a universal of boson-fermioness or perhaps altering the list of first and second-order universals) and our assumptions about property possession (whether objects or spacetime possesses dimensionality will affect their intrinsic and extrinsic properties).

Beyond the open bewilderment about the meaning of dimension, is the further concern that, because of this, we have no real idea how it impacts other elements of our theories, specifically we have no assurances of priority. The evidential underdetermination of theory is a problem for science in general, but it is arguably particularly acute for dimensionality because of both its vague definition and its pervasive and fundamental use (if often tacit) in many theories. If dimensions are only bookkeeping devices then we may have good reasons to think that some laws will hold rather than others and what their effects might look like, but if dimensions are *physically real* and constitutive of the structure of fundamental substances, then it is not clear how we are to construct higher dimensional models on our current definition. As Craig Callender argues,

> Absent a developed physical theory that takes dimensionality as contingent and offers principled physical constraints on what can happen in different dimensions, there seem to be no standards for knowing which laws hold in what dimension. Which is more fundamental, a r^{-1} potential in higher dimensions (and thus stable orbits there) or Gauss' law in higher dimensions (and thus no stable orbits there)? There is no scientific theory of this, and only vague intuitions fill the vacuum (Callender, p.132).

Callender criticises the claims of theorists who take laws or dimensions or matter to be the most fundamental theoretical components and control the variables of the other concepts, arguing that the rationale is only the theorist's belief. In order "to get their conclusion, *some* physics is of course used, *some* assumptions are made, and these assumptions may not be legitimate in higher dimensions, e.g., Burgbacher's assumption that in every dimension the lowest series contains only transitions with l=k=0 or Caruso and Xavier's assumption that classical thermodynamics is valid in all n" (Callender, p.133). This caution of Callender's is particularly salient in the wake of rampant and confident speculation on the nature and characteristics of higher dimensional worlds. There is little or no thought given to what limits or enables the degrees of freedom in one region or by one object compared with another region or object, or to rationales for causal priority, or for a grounding account of what a dimension is physically. While the majority of our attempts to pin down a definition have been broad and brief, it seems as good a place as any to start teasing apart the confusion and see if we can formulate a clearer expression of what we mean by ‘dimension’ (regardless of whether any *real* thing corresponds to that expression, which may also be a matter of underdetermination).

10.2 Traditional and Working definitions of ‘Dimension’

A ‘dimension’ is commonly geometrically described as a direction or axis along which something can move, or equivalently, a dimension offers a piece of information to specify a location. It is in this latter sense that ‘time’ is also viewed as a dimension, since it is such a fundamental component of locating something that it have a temporal component. Geometrically this is typically portrayed by using an additional axis to whatever spatial number is in use (to capture changes in position along a linear temporal ‘direction’). Following these notions, we can look to the literature for particulars; for instance, Swinburne distinguishes between the definitions in geometry and topology, where the former posits that “a space is n-dimensional if and only if *n* real coordinates are necessary and sufficient for unique identification of points” (Swinburne, p.137). He gives the topological definition of a dimension as “defined by the dimension of the neighbourhood of a point of the space, and it by the dimension of its boundary” (Swinburne, p.137), but this only postpones any real definition.

To get a better sense of what our first passes at dimensionality mean, one might try unpacking the terms ‘direction’, ‘motion’ and ‘location’. Thus, we might define ‘direction’ as the straight or curved continuous extent of length (merely a measurement of extent) without breadth along which something moves or faces (e.g. North-Northeast); motion can be defined as a change in position, and location can be defined as the place where something is situated, the assigned particular position—generally relative to other things. If we adopt these terms, then we get a definition comfortably situated in traditional language:

> [1] Dimension= a continuous extent of length along which something may occupy different positions relative to something else.

The key definitions are loaded with co-dependent terms which offer a ‘meaning constellation’ rather than a reductive foundation, but that may at least serve to place ‘dimensionality’ close to other terms we take as fairly primitive. This rather simplistic account of a dimension can be seen as only one particular element of earlier approaches that gave dimensionality a wide scope.

Among the first early modern discourses on dimension is Descartes' broad categorisation, which stems from his aim to give some kind of mathematical formalism to the haphazard world of bodies in motion. By analysing their fundamental characteristics, chief of which is dimension, Descartes argues that the geometrical elements of length, depth and width are arbitrarily distinguished and only one of many ways that something might be measurable. Geometry may not be the best or most accurate way to carve up reality of course, but certainly "physicists have chosen geometry as the currently best way to deal with macroscopic and microscopic mechanics" (Wesson, p.11-12). Whether that sort of division makes the most sense in higher energy physics, or at higher dimensions (if such things would exist in a non-geometrical model) may be disputable.

In parsing away the unimportant features for mathematical reduction, Descartes allows for many aspects of motion and extension to act as a dimension, in much the same way that modern theorists use any piece of information to coordinate the relation of some element among others in abstract spaces. Construed in this way, dimension is a feature applicable to more than just spatial extension; "thus it is not merely the case that length, breadth and depth are dimensions; but weight is also a dimension…So, too, speed is a dimension of motion…it clearly follows that there may be an *infinite* number of dimensions" (Rules for Direction, XIV, *Philosophical Works*, I, 6I (AT X, 44-48)). This early definition has persisted both in the common usage of dimension as an aspect of something and in physics as 'dimensional analysis' where useful physical quantities are calculated using what are called basic physical dimensions (including determinations of time, mass, length or even temperature and charge) that speak in very different terms than geometrical orthogonality.

Nonetheless, dimensional analysis does preserve both the idea that a dimension involves a piece of information and a means of 'locating' an object in a space (even if it is not always clear if the space is physically real) by means of independent variables. For instance, to locate a particle one may need a value for its mass as well as its charge, either of which may change without affecting the other, such that each value can be seen as a separate dimension. The Oxford Dictionary of English notes all three meanings in its 'dimension' citation, providing a first pass at our working understanding of the term:

dimension *noun*

… (usu. Dimensions) a measurable extent of a particular kind, such as length, breadth, depth, or height: the final dimensions of the pond were 14 ft x 8 ft | [mass noun] … ■ a mode of linear extension of which there are three in space and two on a flat surface, which corresponds to one of a set of coordinates specifying the position of a point. ■ (Physics) an expression for a derived physical quantity in terms of fundamental quantities such as mass, length, or time, raised to the appropriate power (acceleration, for example, having the dimension of length × time^{-2}) (Oxford Dictionary of English 'dimension *noun*')

Although the latter sense of dimensionality is commonly attributed to physics, the discipline also heavily relies on the more standardly geometric account, particularly as concerns the spatial structure of reality:

> A mode of linear measurement, magnitude, or extension, in a particular direction; usually as co-existing with similar measurements or extensions in other directions.
>
> The three dimensions of a body, or of ordinary space, are length, breadth, and thickness (or depth); a surface has only two dimensions (length and breadth); a line only one (length). Here the notion of measurement or magnitude is commonly lost, and the word denotes merely a particular mode of spatial extension. Modern mathematicians have speculated as to the possibility of more than three dimensions of space (OED online 'dimension *n*').

The depth of the above OED definition is largely comparable to the non-mathematical ones given by scientists and theorists, and gives us little insight into the constituents or criteria for a physical dimension. It is not only through physics directly, however, that we need investigate what we mean by the term, indeed more of the meaning might be teased out by focused analyses from surrounding fields that treat dimensionality in the same spirit as the above definition.

An early non-scientific approach at constructing a definition of dimension comes from Benjamin Gilman (Gilman 1928), who attempts to set out a definition for a one-dimensional manifold, where a 'manifold' can be any plurality of things, and whereby it will be the particular relations that these things, or 'elements' bear to each other that will determine their dimensionality. For Gilman, "a manifold may be such that every pair of its elements subsists in one certain relation. The relation may then be termed 'characteristic' of the manifold. When a characteristic relation is both heterogeneous and transitive, it is called a 'dimension' of the manifold it characterizes. Let such a manifold be called a *one-dimensional* manifold" (Gilman, p.562-3). By 'heterogeneous', Gilman means that the relation each term of a 2-part relation bears to the other is different, that is, what we might now call asymmetrical; for instance, the relation X is 'larger than' Y gives X a different relation to Y than Y bears toward X. If the relation were the same, as with the relation of 'equivalence', then Gilman would characterise the relationship as homogenous (symmetrical).

By 'transitive', Gilman more straightforwardly means that if X bears a relation *r* to Y, and Y bears relation *r* to Z, then X bears relation *r* to Z. More generally, then, a dimension is defined through the particular transitive and heterogeneous characteristic that is "necessary and sufficient to describe the relation in which every element of a given manifold subsists with every other" (Gilman, p.574). He intends this definition to apply to the number line, to time, physical space, or indeed to the lineage of English kings. Thus, English royalty is a one-dimensional manifold, where every "predecessor differs from successor, and the predecessor of a predecessor is also a predecessor" (Gilman, p.568). From Gilman we gain the idea of sequence and a primitive sense of connectivity that does not obviously transfer to higher dimensional manifolds. Indeed although the idea of sequence is more easily adopted into later set-theoretic accounts that underlie modern conceptions of sequences like the number line, spatial connectivity has been largely glossed over. Nonetheless, let us take his account as a cursory operating definition of dimension:

> [2] Dimension = a certain relation that is both heterogeneous and transitive which is possessed of all the elements of a manifold.

Clearly [2] gives no particular emphasis to a physically real spatial account, but beyond that it does little to elaborate on the relevant kind of relation, connection, or the relata (which might be, say, spacetime points or material entities). To make it applicable to more complex spaces than a one-dimensional manifold, we might add to the number of relata (e.g. further specifying the dimensionality through the 2- or 3- or 4- etc. part relations—n-tuples—of the manifold).

[3] Dimension = a certain n-tuple relation that is both heterogeneous and transitive which is possessed of all the elements of a manifold[83].

This n-tuple relation gives us the flexibility of increasing the data points (the coordinates, or independent pieces of information) to accommodate higher dimensions, but it does not convey any notion of how that relation impacts the dimensionality or in what it consists. The nature of the relation would itself be an interesting idea to pursue, perhaps giving physicists a clearer set of criteria for distinguishing and explaining dimensions. For instance, the n-tuple relation between elements might be purely distributive with one element bearing the same relationship to several other elements (as a mother would to all her children); or purely collective with one element bearing a relation to a collection of elements (as the 'centre of a circle' bears to all the points that make up the circle, or when Tom, Dick and Harry *surround* a house which they could not do individually); or a variety of relations[84]. Our simplistic account of dimensions (invoking the examples of a line, square and cube) seem to favour the distributive approach at first blush, but that may change on closer inspection or upon reflection of the higher-dimensional characterisations. Beyond the kind of relation, one might also incorporate how we think interconnectivity impacts the dimensionality.

10.2.1 Connectivity

A more recent take on dimensions that focuses much more explicitly on information theory and the study of networks, gives particular attention to the connectivity aspect of dimensionality. Although it is not clear whether the adopted notion of dimension is elaborating on the physicist's definition or importantly diverging, it is of central importance to 'systems', as Daqing et al. note: "the dimension of a system is one of the most fundamental quantities to characterize its structure and basic physical properties. Diffusion and vibrational excitations, for example, as well as the universal features of a system near a critical point depend crucially on its dimension" (Daqing et al., p.1). In their study of networks of embedded dimensionality, they argue that networks of widely distributed, long range connectivity between nodes are of a higher dimension (and even arguably infinite) than networks of short range linkages connecting only nearby nodes. The networks are able to

[83] Spacetime manifolds and metrics are features, or structures, of spacetime such that "a space which carries consistent continuous coordinates is called a *manifold.* In addition to being a manifold, real space has *geometrical* structure…Furthermore, *distances* and *angles* may be defined. Spaces with these features are called *metric spaces*" (P.C.W. Davies, p.11).
[84] Particular thanks to Katherine Hawley for raising these suggestions [and throughout!].

transcend the surrounding spatial dimension through such long range inter-connectivity, whereas in networks connecting "only neighbouring nodes (in space)…the dimension of the network is trivially identical to the dimension of the embedding space" (Daqing et al., p.1).

The above account makes connectivity the hallmark of dimensionality, with spaces (networks) of dense interconnectivity acquiring a higher dimension than spaces of marginal connectivity. The account also employs formulae that take both the number of nodes and the probability of 'encountering' one at a certain distance to scale with the dimensionality. Phillip Bricker, too, raises concerns about connectivity, wondering if there are "direct ties only between 'neighbouring' points, so that points at a distance are connected only indirectly through a series of such direct ties? Or are there also direct ties between distant points, so that the fabric is reinforced, as it were, by irreducibly global spatial relations?" (Bricker, p.271).

This 'reinforcing' could certainly contribute to the density of spatial pathways, and presumably increase the dimensionality of the space. Although undertaking a different project, Nerlich suggests an intrinsic account of directions and non-overlapping paths that also seems well formulated to capture some of this path-wise connectivity of dimensions. He argues that "the set of directions round any point in physical space is intrinsic to it…the directions are not tangent vectors…A direction at a point is shared by paths which touch at the point without crossing" (Nerlich, p.105). This notion of non-intersecting paths (where traversal along every path could be undergone simultaneously) offers another component to our understanding of dimensionality and highlights the importance of the relations between pathways.

This interest can also be seen in modern and rather exotic variations of loop quantum gravity, which includes a discrete spin network composed of evolving intersections of looping flux-lines that models spacetime at its smallest level; "the area of a given surface is determined by the number of 'edges' of the network it crosses (not the expanse of interior void), and the volume it encloses is given by the number of nodes (or intersections) it contains" (Dainton, p.333). This importantly incorporates interconnectivity into a conception of physical density, perhaps providing another clue as to the nature of dimensionality. Such network edges appear to be the pathways that 'channel' energy and objects, effectively giving boundaries to space, while the nodal density (and presumably the nodal orientation) establishes spatial volumes and the structure for higher dimensions in this model. One of the most important aspects of dimensionality is to characterise the ways objects can (or cannot) interact, and in loop quantum gravity we find this modelled in "the way these loops and lines intersect and knot together [which] determines the geometry of space at the Planck-scale" (Dainton, p.333). Another important characteristic that this theory raises is that of the fundamental divisibility of spacetime; that is, whether spacetime is discrete—offering a maximum density for a region or even giving rise to space itself through certain 'looping' structures—or whether spacetime is continuous and follows classical mathematics.

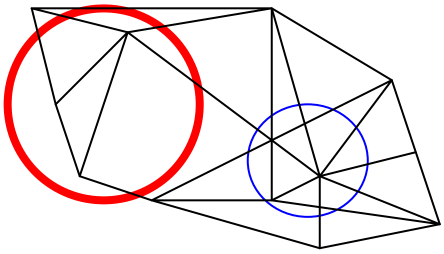

Figure 4. Although the thick circle is larger it covers a smaller area and volume in the spin network than the thin circle (which encompasses more edges and nodes).

This concern over the basic model for spacetime units, may have pressing implications for dimensionality. When it comes to our conception of dimensions, more often than not continuity is assumed rather than questioned. Mathematicians like Poincaré only give recursive definitions of 'dimension' that "deal explicitly with continuum…and assigning three dimensions to space on the basis of these definitions means adoption of the continuous structure of space from the outset" (Abramenko, p.91). But the strength of the quantum model over the last century has slowly worn away the confidence in continuity as discrete models (from energy and motion) seem better equipped to explain phenomena.

Which model we adopt certainly can affect our theories, and some theorists, like Abramenko argue that continuity is critical to our common notions of dimensionality, even though continuity in space and time remains an unverified (and dubious) postulate. If space or time adopted a discrete structure, he argues that "the usual meaning of dimensionality will be lost, and physical discontinuous time [or space] will be represented by a zero-dimensional complex of cells" (Abramenko, p.104). It may also be the case that a firm understanding of dimensionality is ineliminably bound up with a clear understanding of the basic model of divisibility (whether discrete or continuous).

Taking such models on board, we might try to insert our concern for connectivity and the pathways available, particularly as concerns the number of relata. Thus we might expand [3] with:

> [4] Dimension = a certain n-tuple relation that is both heterogeneous and transitive which is possessed of all the elements of a manifold, and is distinguished by the number of independent paths (degrees of freedom) available to those elements.

While incorporating the degrees of freedom may reflect general attitudes to dimensionality, degrees of freedom need not be limited to the orthogonal specifications of earlier accounts. For instance, physics often takes a degree of freedom to be any independent physical parameter (often geometrically *represented* as an orthogonal axis) in the formal description of the state of a physical system. A system of N independent particles in 3-dimensions, therefore, has the total of 3N degrees of freedom[85]. If we were to simply equate 'dimension' with 'degree of freedom' along these lines then the dimensionality of any space would directly depend on the number of unique entities moving in distinct directions (independent pathways).

This focus on connectivity can be found in other notions of dimension, where it is described by the degrees of freedom for a point or object that are not dependent on other variables. The degree of freedom—which the mathematician Shin-Tung Yau *defines* as a dimension, "an independent way of moving in space" (Yau, p.3)—represents a path in a network, and in this respect bears a strong similarity to dimensional analysis carried out by Daqing et alia. Might we then be able to determine the dimension of a spatial region simply be counting the possible degrees of freedom from any chosen node or average set of nodes? Although this seems to aim only at differentiating a hierarchy of dimensions, rather than defining them, it may provide a useful insight into the latter. Were we to take this approach we would need to first decide 1) what counts as a node (or element) and 2) what counts as a path or degree of freedom (which will also include determining what sorts of things are to 'traverse' these paths). If we want to preserve the heterogeneous and transitivity requirements of Gilman, our method of determining spatial dimension might further specify that these paths are distinguished in at least their spatial positions as categorised in our 3-

[85] Dimensions in Hilbert space, for instance, follow such a model, wherein the notion of dimension is built out of state-vectors which can be "linearly independent of the rest. The size of the largest set of mutually linearly independent state-vectors is then the dimension of the Hilbert space…Hilbert spaces are vector spaces over the field of complex numbers and…their dimension may be any integer from 1 to a countable infinity" (Gibbins, p.90).

space (or by another means) and that this same relation is found between all points within the dimension.

So while something of this idea could be incorporated, it is unclear how exactly this should be applied and whether, for instance, we should take an average of the available independent paths if they differ for the elements in a given region, or simply take the highest dimension manifested (or physically possible) in that space. However, it does seem that the *interconnectivity* of those independent pathways can be an important indicator of dimension even with our simplistic accounts. Where two pathways intersect, the freedom of movement cannot be maintained unless that intersection becomes a higher-dimensional crossover, that is, at least a 3-dimensional space.

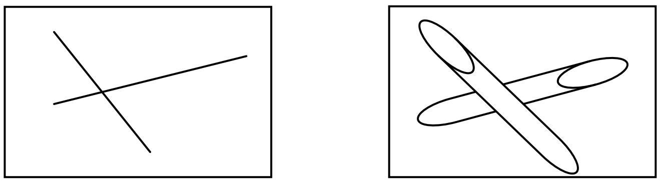

Figure 5. Crossing pathways in 2 and 3 dimensions

If this approach holds through higher dimensions then the more pathways to 'intersect', the more dimensions are needed to account for the degrees of freedom. Certainly our expectations for interconnectivity will be a concept to flesh out, but if it is to be an essential component, presumably it should at least capture the idea of dimensional accumulation, as each higher dimension partakes of all the connectivity of the lower ones as well as adding its own links to the 'nodes' of each lower dimension. For instance, we can think of each point on a line mapping onto another set of points perpendicular to the original line to form a plane, as well as having each point on the mapped plane (including that one-dimensional line) map onto another point-set perpendicular to the plane and forming a cube. The cube will thus allow for connections between the nodes of the line *and* plane *and* all its own additional nodes, exponentially increasing the connectivity of the space. This approach does not seem contradictory to our other working definitions of dimension (e.g. as an extension in a certain direction), but it is still a long way from giving a precise account of its terms. This attempt is necessarily cursory, however, and may improve upon a better understanding of how we use dimensions, which I will now survey.

CHAPTER 11: Ways we Use Dimensions

Perhaps because of our fuzzy conception of 'dimension' we employ the term to do a lot of work, invoking dimensions to help explain separation, transmission, the general way our universe is, geometrical analysis, informational organisation and property attribution. This is an impressive list that should catch any metaphysician's eye, and although I will here only give an overview of some of the term's uses, the richness should be clear. First, dimensionality offers a means of keeping things separate or in contact; second, dimensions are crucial in attempted constructions of a unified fundamental physical theory whereby the forces and perhaps their particles are reduced to the same laws and substance; third, dimensions are common mathematical and geometrical devices; finally, dimensions are used to order and transmit information.

11.1 Contact and Separation

One of the more important motivations for discussing dimensionality has been to account for our own *observed* tri-dimensional world, although more recent decades have seen the motivation switch to account for the possibility of inhabiting higher-dimensional worlds. Regardless of the particular number one settles on, the dimensionality of a space is seen to offer an explanation for various observations, such as our conception of causation as spatiotemporally contiguous. Nerlich supports this explanatory role, arguing that "we say that space has three dimensions because only that choice lets us describe the world so that the action is always by contact (or causal transmission)" (Nerlich, 1994, p.192). There are other assumptions built into Nerlich's claim, since presumably we could still describe the world so that action is through contact even in five dimensions—and he certainly offers no proof that this could not be the case. Overlooking, for the moment, the rationale for this statement (part of the concern, of course, is that our understanding of dimensions is so poor we do not know which way the explanation goes), we do find 'dimension' accounting for physical phenomena, whether it is action-through-contact or the stability of planetary orbits (Barrow, p.338). In the same capacity that dimensions can account for contact, however, they can also be a means of separation, and in this respect seem intimately tied to a fundamental role of space in general.

Dimensions offer us a nearly magical means of controlling how and if entities interact, allowing us a plurality of closed-off or very close worlds in otherwise undistinguished space. In particular, "extra dimensions introduce a way to separate particles" (Randall, p.335). Following this approach, Nerlich suggests that "just as orientability is displayed in a difference between left and right hands, dimensional features are displayed in action by contact – or better, by the kind of physical thing that can be a boundary" (Nerlich, p.152). This last qualification is fairly mysterious, and Nerlich does not elaborate, but we might try to interpret it as noting the way dimensions 'cut off' certain interactions between certain objects and act as boundaries. Suppose I put two 2D creatures 50 centimetres apart on a plane, and further that I hold another 2D creature 3 centimetres *above* one of the other creatures.

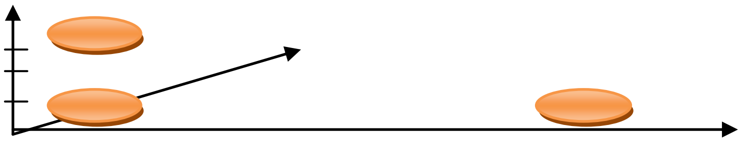

Figure 6. 2D creatures 'stuck' to a plane and one held above.

Although the distance between the held-creature and the one below it is much less than the distance between the creatures on the plane, there may be no means of leaving the plane for a higher dimension (perhaps a restrictive law of motion for 2D beings), which makes the more-distant (all space considered) 2D creature closer in terms of accessibility to the other plane-bound 2D creature than the one I hold. Dimensional pathways create conduits as much as barriers. This remarkable property of separation allows dimensions to shape the connective paths between the nodes, or elements, of a space, preventing some objects from having certain types of interactions and locations. I say this with a seeming bias toward space bearing the property of dimensionality, but of course it may be the objects themselves that attain the dimensionality, and thus directly determine the type of interactions allowed amongst themselves (space may additionally be seen as either dimensionless or infinitely dimensional). One can adopt either assumption about the source of dimensionality, and allow that the nodes of dimensional connectivity and separation may be objects as much as spacetime points/regions. In either case, dimensionality can offer a further set of rules governing the interactions of objects.

11.2 Unification and the Universe

One of the most exciting uses of dimensions, and dimensional structure is the possibility of unifying seemingly disparate properties and fundamental forces, as well as offering more exotic options for higher dimensional 'directions' that can more cohesively explain physical law. The ideological benefits of such explanatory unification (and presumably predictive success) seem far more tantalizing to many than the acquiring of a greater dimensional ontology is burdensome. For instance, in extending Kaluza's theory, Oscar Klein suggested that "macroscopic objects are confined to four-dimensional space-time, but elementary particles have what physicists call a higher degree of freedom: we can think of particles as capable of moving around this fifth coordinate in either direction. If they go around one way, they are positively charged; if they go the other way, they are negatively charged" (Gardner, p.236). Of course, taking this analogy to a lower level is difficult because we do not appear to move in higher dimensions but remain always in 'three-space', and we can not know if our moving up or down would produce a charge-like property to a two-dimensional observer.

The supposition remains, however, that dimensions may reveal the array of fundamental properties to be much more limited and unified, manifesting in a diverse number of ways only when viewed from restricted dimensional perspectives. This ought to raise further concerns for questions of intrinsicality in a variety of ways including whether we are justified—by our own analysis—in regarding three-dimensional 'position' as an extrinsic feature, when a ten or eleven-dimensional framework might recast that 'position' as some sort of, say, 'intrinsic spin'. Intrinsicality in a unified higher-dimensional account might then have to adopt relatively complex property descriptions that allow for such symmetry translations as fermions to bosons. Alternatively, we may feel no more compelled to make our property ascriptions cover such a range and may choose instead to carve our reality up along a different set of objects, but in either case dimensions seem to figure in the analysis.

11.3 Geometrical and physical tool

The mathematical use and understanding of dimensions often drives the account given them by other disciplines, even when those representations are ill-fitted to the new material. But it is partially this relative simplicity and abstraction in mathematics that makes dimensions so useful and encourages us to use them in innovative and fruitful ways. For some, dimensions are something of a possible worlds testing ground for theories, a means of exploring 'intrinsic' geometric or topological properties whereby "to truly understand a concept in geometry, such as curvature or distance, we need to understand it in all possible dimensions…the point being that if a rule or law of nature works in a space of any dimension, it's more powerful, and seemingly more fundamental, than a statement that only applies in a particular setting" (Yau, p.4). Even though we cannot be sure how laws of nature behave in extended dimensions and are left with Callender's concern about biased principles of primacy, the pairing of dimensionality with geometry is an important tool; geometry has long been privileged as the best way of understanding and representing the relations of objects and space, and as such provides the most pertinent accounts of dimensions for our purposes.

The dimensional analysis of physics has adapted the geometrical concept to its more abstract spaces and new coordinates, which physicist Jonathan Graves sees as entirely separate from the geometric account. He thus distinguishes two senses of dimension where "the first sense of dimension (dimension$_1$) is a purely geometrical one…This is the sense used when we say that space has three dimensions, that space-time has four dimensions, or that a surface has two. Here all the dimensions are assumed to be similar in kind, and perfectly commensurate with each other" (Graves, p.198). The second sense of dimension (dimension$_2$), such as the dimension of a physical magnitude, is more like a *type* "of dimension in the first sense…In distinguishing these dimensions$_2$, we assume explicitly that they are qualitatively different and incommensurable. We cannot add quantities with different dimensions and expect a meaningful result" (Graves, p.200).

By dimensions$_2$ Graves means the qualities used in physics' dimensional analysis and which can be seen as the successors of Descartes' account. For instance, among the most common basic dimensions are properties like mass, length and time, each of which offers an independent variable used to fundamentally describe the most basic constituents of matter. The above dimensions$_2$ may combine, say, in the form $M^{\alpha}L^{\beta}T^{\gamma}$, which can then be used to define other measurements like momentum $M^{1}L^{1}T^{-1}$ or the gravitational constant, $M^{-1}L^{3}T^{-2}$. Dimensions$_2$, then, refer to "the most general and irreducible distinctions in the descriptive framework provided by the *model*" (Graves, p.201), whatever model is employed. This system of dimensions reflects the success of Newtonian mechanics that put such values at its core, but they need not be essential to the conceptual framework and can be replaced by more nuanced 'dimensions' (e.g. 'spin').

From this much abbreviated overview of the traditional and working definitions of dimension, we not only find two different senses of the word—as a geometrical term or as that used in dimensional analysis—we also find a fairly superficial notion of how either sense applies to reality. I will focus on the geometrical (dimension$_1$) sense because it seems to best describe our apparent three-dimensional world and touch on something fundamental in our metaphysical view. But the lack of a formalised rigorous account of dimensionality means that there remains a large gap in understanding the concept in physically real terms. Indeed, there are reasons to suppose dimensions to be merely bookkeeping devices, instruments to help our understanding of the universe. Even those that see dimensions as more than organisational tools still speak of them in terms of pieces of information or mathematical models, rather than in terms of physical entities. Classifying in terms of information is a popular approach, however, and importantly allies with dimensionality.

11.4 Ordering information

For instrumentalists and realists alike, one of the central functions (if not *the* function) of dimensionality is as an organiser of certain types of information, and in this "a dimension is more than a collection of points: it is a way of organizing things according to whether they are nearby or far apart" (Randall, p.315). This distinction is important, since it is very much about how things are related rather than how many things there are[86], and this association goes back to the 19th century that saw a boom in the mathematical exploration of dimensions, which similarly became increasingly involved with the idea of information; "Cayley, Riemann and others developed the systematic study of N-dimensional geometry although the notion of dimension they employed was entirely intuitive. It sufficed for them to regard dimension as the number of independent pieces of information required for a unique specification of a point in some coordinate system" (Barrow, p.337).

Such required information has come to include non-geometrical features, or rather, we have come to see the geometry of higher-dimensional space in terms of non-geometric features (at least in our observable world). The quantum uncertainty of pinning down an object (or point of that object) in space has shown physicists that position can depend upon other values like momentum, encouraging a broader understanding of information than a Euclidean coordinate system implies. This widening of the *kind* of information admissible for the specification of dimension might make the association of the two concepts seem like a platitude; the organisation of information could be said to account for most things. Information remains, however, the most common descriptor of dimensionality. From Eddington we learn that "on any surface it requires two independent numbers or 'coordinates'

[86] As noted by Eddington: "An aggregate of a large number of things has in itself no particular number of dimensions. In order to define the number of dimensions we have to postulate some ordering relation. This relation appears to be the interval" (Eddington p.186).

to specify the position of a point. *For this reason* a surface, whether flat or curved, is called a two dimensional space" (emphasis mine, Eddington, p.77). This same principle extends to non-spatial dimensionality as well, such that we specify events with "*four* pieces of information: three in space and one in time…in this sense, time is another dimension" (Greene, 1999, p.49-50). Although important to our working conception of dimensionality, the *physical* information required to locate an object is not intuitively obvious when we look at higher dimensional spaces, and this seems to encourage physicists to investigate more abstract *mathematical* information.

Mathematicians have embraced the expanding notion of information not by examining physical phenomena but by giving every term in their calculations a dimension of its own. Dispensing with the maximised geometrical efficiency of orthogonal coordinates, mathematicians commonly take each direction of movement by an object as its own *abstract* dimension. Thus, "in describing all the ways that one thousand atoms can be arranged in a molecule …we need to give three thousand numbers, which we can think of as the coordinates of a three-thousand-dimensional landscape" (Susskind, p.275). There are more abstract 'symmetry dimensions' that follow the same pattern, whereby the number of relevant particles (say, that communicate the studied force) corresponds to the number of (symmetry) dimensions. For instance, "E_8 is a 248-dimensional symmetry group that can be thought of, in turn, as a gauge field with 248 components (much as a vector pointing in some arbitrary direction in three dimensions has 3 components – described as the *x*, *y* and *z* components)" (Yau, p.206).

The mathematical approach does seem to capture the idea of a degree of freedom, but it challenges our traditional conception of dimensions as pervasive spatial structures. For mathematicians, a point in 4-dimensional space may simply be the set of data consisting of four variables: x, y, z, t. In this abstract 4-space one can extend the properties of *mathematical* objects in lower dimensions and determine, say, which edges connect which vertices in 4-D regular polyhedra, even if one cannot be confident about the structure of *physical* objects undergoing analogous changes. Indeed, the mathematical equivalence between a group of 248 objects and a 248-dimensional space does not seem to obviously carry over to the physical world, and while we may wonder which view is correct, if either, we may also wonder how some qualities are in any way commensurate—how dimensional coordinates in one framework are unique objects in another framework.

The preference extends beyond abstract Euclidean geometry, however, with physicists choosing to interpret 'fundamental' values and quantum states "in a geometrical way – the states of a system corresponding to directions in space (a space of many possible dimensions), and their distinguishability depending on whether those directions are perpendicular" (Gleick, 2011, p.365). But is this interpretation misleading? Consider James Bond. Bond is an entity who has greater clearance than me; he is able to access areas I am forbidden from entering, and can travel from point A to point B (say, Rome to Rio) faster than I can travel it. Does this mean Bond is a higher dimensional entity than me? To give him this distinction *is* getting at some difference in the world, but what kind of difference? All objects like me may have to follow these restricted rules and behaviour, and all objects like James Bond may have to follow *that* behaviour, and is that all we mean by dimension? It seems much more likely that we will give it more fundamental weight if there is either 1) a physical substance of space that is contoured to force these different behaviours or 2) enough elements to warrant dubbing this relation a 'law'. One might argue that the infamous agent James Bond operates on a sufficiently different level than I do—with higher clearance and permission to access typically forbidden 'domains'—that he merits the introduction of a structural distinction—a dimension—to explain his behaviour. Then again, this may be only a matter of intuitions in need of a much more stringent definition.

Mathematicians certainly paved the way for dimensional acceptance, and such information on position in a geometric model perhaps once seemed among the more objective attributions an object could have—colour or sharpness or teleological worth all seem too anthropocentric and changeable to be considered. But relative notions of position, uncertainty over the interpretation of values and concerns about what kind of coordinates in what kind of space can be used as objective data on geometric position have complicated matters. Particularly, Riemann's association of dimensionality with the number of coordinates needed to locate an object (or characterise a position) in space "was undermined by the nineteenth century discovery that a single continuous line could completely fill (and hence be used to coordinatize) a two-dimensional square" (Dainton, p.353).

This demonstration by Georg Cantor that the line's set of points and the plane's set of points are equinumerous may have encouraged the subsequent description of a dimension in terms of ‘degrees of freedom’,[87] which happens to fit the ‘information paradigm’ quite well. The abstract flexibility of information (coupled with dimensionality’s vague definition) poses acute problems for physicists, however, who may find themselves agreeing with Randall’s sentiment that “duality still makes me wonder what the word ‘dimensions’ really means. We know that the number of dimensions should be the number of quantities you need to specify the location of an object. But are we always sure we know which quantities to count?” (Randall, p.450).

Any number of mathematical dimensions can be entertained, but their relevance to physical reality typically rests on the fundamental constants of Planck, Gravity or the speed of light. These parameters can be used in higher dimensional analysis “to change the physical units of material quantities to lengths, enabling them to be given a geometrical description” (Wesson, p.14). For instance, one might interpret mass and charge as extra dimensions of space—as an ‘extension’ of the same sort as length and height. But as Graves notes, this is problematic, since “bodies already have characteristic geometrical lengths, describing their size and shape…what then is the orientation (or direction) of these new dynamical lengths with respect to the old ones of width, depth, etc.?” (Graves, p.206).

Such collusion would need a new system that can integrate the perceptual geometric structure with the dynamic parameters, which may be “trying to fit them into one space when there are really two” (Graves, p.206). This uncertainty about what sort of things can count as dimensional variables is fairly acute, such that including the property of ‘momentum’ could be seen as trying to put too many parameters (mass and velocity) into one space. It is also unclear what implications, if any, these extra dimensions would have for spacetime itself (e.g. does it offer a new degree of freedom at every point?). Taking such talk to be only a convenience, however, an instrumental device for prediction, say, would remove the ontological concerns, giving us another framework to make sense of information, but even then we need some sort of direction to pick out the relevant variables.

The values that appear to merit their own dimensions are fundamentals of physics like charge, momentum (which thereby takes mass and velocity into account), time and perhaps spin. We seem to apply this approach to other cases where we invoke dimensions, accepting that the fundamental variables alter according to the desired scale and sphere of interest:

[87] For instance, taking ‘place’ to mean roughly a set of points, Benjamin Pierce is cited as offering several definitions including “the Freedom, or Number of degrees of freedom of a place, subject to certain conditions is the number of independent singly continuous motions of which it or its parts are susceptible” (Dipert, p.64).

> Each point of our ordinary space can be topologically characterized by three, but not less than three, real numbers, *e.g.*, its Cartesian or spherical coordinates….Similarly, each color sensation of a normal eye can be topologically characterized by three, but not less than three, real numbers, *viz*., the quantities of three standard colors whose mixture produces an identical sensation. Hence, the totality of color sensations of a normal eye is 3-dimensional while the corresponding totalities for a partially or totally color blind eye are but 2- and 1-dimensional, respectively. In the same way, a totality of all mixtures of four ingredients which cannot be obtained by mixing less than four of them is called four-dimensional. In fact, in this direction lies our only elementary analytical approach to…higher-dimensional spaces (Menger, p.2-3).

Part of the question, then, is deciding what information best uniquely describes an object. By analogy, dimensions are characterized by the values sufficient to go from a book's index to the desired quote. Despite colloquialisms to the contrary, complex, dependent qualities like colour are not considered in physics, presumably because it applies to aggregates (and not, say, *an* electron) and is not as efficient at geometrically locating an object. Even though the geometric approach fails to specify which values we need to take into account to locate an object in a higher-dimensional space—and this uncertainty should concern us—we are still committed to the idea that the organisation of information specifies and perhaps demands a certain dimensionality.

11.4.1 Information transmission

One of the most important interactions that dimensions play a role in governing is the transmission of information, both broadly construed in terms of matter and actions as pieces of data and narrowly construed in the sense of signalling and communication. Under the broader conception, one of the chief uses for higher dimensions is as an information store, a place to hold data, such that very energetic particles with complex behaviours can be given enough 'space' to move about. For example, it was argued early in the 20th century that Schrodinger's theory required an additional band of frequency, "as phenomena of incoherence cannot occur in strictly monochromatic oscillatory phenomena. *We thus see a definite reason for introducing a fifth dimension, to give room for this band*" (Weiner and Struik, p.264). In this way, one can see the needs of independent information (space for a band of frequency) driving the more extensive dimensional ontology.

The information content of a system is bound up with many other concepts, including dimensions and is another description for entropy, such that when the entropy content rises so too does the information required to describe the system. Determining what type of information is relevant (momentum, geometry, size, charge?) and which types are independent spectra from the rest, then, importantly relates to the number of dimensions, and is very much a key issue. Not only does the connective structure given by dimensions store information, but the limits on information transmission are thought to be set by dimensions as well. In this respect dimensionality may allow or prohibit the development of many complex and precise constructions. For instance, following others John Barrow argues that

> it is impossible to transmit sharply defined signals in two dimensions, for example, by waves on a liquid surface. Now it is known that the transmission of wave impulses in a reverberation-free fashion is impossible in spaces with an even number of dimensions (Hadamard 1923). The favourable odd dimensional cases are said to obey Huygen's Principle (Courant & Hilbert 1962). This situation has led many to suppose that life could only exist in an odd dimensional world because living organisms require high fidelity information transmission at a neurological or mechanical level (Barrow, p.341).

The mathematical expectations and interpretations of dimensions weigh heavily in this analysis, nonetheless, it is another significant way in which dimensions are thought to shape our world by requiring certain connectivity structures for certain processes, particularly for the transmission of high definition information as we know it.

Perhaps a more immediate example can be seen in an attempt to describe our world from an ignorant 2-dimensional scientist's perspective, using, say, the surface of the earth as the plane in question. Like physicists working in higher dimensions such an endeavour may be able to arrive at a complex mathematical method for capturing most, if not all, of the information we find significant now, but it will necessarily involve unfamiliar characterisation. For instance, there will be times when foot-shaped movements are recorded with some disturbing the plane more than others, perhaps engendering a 2-dimensional concept of mass. The information stored in our 'footprints' will thus be circumscribed and perhaps yield significantly different structures and causal accounts than in our 3-dimensional approach. Rules that govern the movement or even type of energy—and thus information and signals—will have a drastic effect on the kinds and complexity of structures and processes permitted in a given world. But all of this, of course, rests on whether we adopt a realist or instrumentalist account of dimensions, as examined in the next chapter.

CHAPTER 12: The Status of Dimensions

Despite claims that it is a bad question to ask, in my view, one of the most interesting questions attendant to the rise of dimensionality is one that revolves around whether we are to take a realist or instrumentalist approach. This, along with a look at whether spatial structure is the bearer, or objects themselves are the bearers, of 'dimensional properties' will be raised, with modest aims of clearing the field to open discussion.

12.1 Instrumental

Dimensions may be, like the mathematical number line, simply an instrument, a way we make sense of the world, without having any physically real presence. They may be just a useful name for a grouping of phenomena, much as our biological taxonomy designates a class of organisms as 'oysters' that nonetheless do not feature in our best physics. This is in contrast to other theories that claim *physical* dimensions do feature in our best physics, perhaps even as a structural component, and that they help *determine* other basic properties. Part of the confusion is that our mathematical formalism does not guarantee or dictate ontology, and it is often its mathematical uses—and flexibility—that obscure a clear ontological interpretation, leading to underdetermination in our theories (as discussed).

Because so much hangs on which of these definitions we adopt, we should make an effort to choose, or at least to give an account of how we would choose. Thus, part of our enquiry concerns the extent to which dimensions provide a model *for* reality or a basic structural component *of* that reality. The reasons for endorsing only the former might include dimensionality's vague definition discussed earlier, as well as the lack of empirical support, the suspicion that questions on the nature of dimensionality are misguided, and the often endorsed possibility that 'dimension-talk' only arose for general utility in scientific practice, particularly as concerns mathematical tractability.

The vague definition of 'dimension' in some ways supports the instrumentalist stance as it can be taken as an indication that there is no physical entity there to guide the construction of a definition (it is much more difficult to confirm something exists if you do not know what *exactly* you are confirming), but it is not the only or even the strongest argument for such an approach. It does not seem too outlandish to chalk up the customary division of our world into three spatial dimensions to a mere instrumentalist tool just as we might divide the world into ‘animal’, ‘mineral’, ‘vegetable’, or the cardinal directions. Dispensing with any fundamental slicing of ‘directions’ couples nicely with the present lack of empirical verification of higher-dimensional structures to our space, while the challenge of even constructing experiments that might be able to confirm them leaves ample room for scepticism.

For instance, one current model (and there are many) posits the existence of six rolled-up dimensions at every ‘point’ in our observable 4-dimensional spacetime, but “every attempt to move an object in the direction of one of the compactified dimensions will see it revert to its original position after about 10^{-40}cm; and since this path is unimaginably short, we do not know whether our object has moved at all” (Genz, p.259). That dimensions could be so elusive and exotic certainly raises questions about their nature, how they interact with matter, and what it is that is getting compactified, but it also gives us reasonable cause to suspect that we are using dimensionality to account for a variety of phenomena that rest on some other physical foundation.

Many are quick to call the enterprise of determining the ontological significance of dimensions confused from the start—a bad question—and it is a criticism levied at more theoretical entities than just dimensions. For instance, if asking about the physical reality of twistors in Roger Penrose’s twistor theory, one might be told that “this is a vague question, like asking whether a planet’s elliptical orbit is real…It is best not to worry about such metaphysical questions, but to think of twistor theory as a new mathematical technique…” (Gardner, p.255). This seems a fine position to adopt if one is a mathematician, but altogether disingenuous if one is a physicist, and the analogy could certainly be drawn with queries on the ontological status of dimensions.

Presumably such thinking is partly behind the relative lack of work done on dimensions, but even if one doubts that a comprehensive realist account can or should be given, they ought to be concerned, I argue, with whether they are treated consistently in scientific discourse, particularly because it has implications for the attribution of properties, ontological dependence and the way we construct our best physics. Just as we have found it fruitful to determine whether the ether, the Higgs field, or Pluto is physically real, I think we have good cause to determine both what we mean by dimensions and, if it is then appropriate, whether they are physically real. I thus wholly reject the idea that such pursuits are born of a ‘bad question’ and would expect those that argue dimensions to be bookkeeping devices to offer a better rationale.

In one of the few focused accounts on this subject, Paul Wesson reviews ways in which dimensional treatment in the sciences favours an instrumental interpretation. Noting the flexibility of the term, he argues that dimensions are “subjective but essential concepts which provide a kind of book-keeping device” (Wesson, p.2). In observing the adaptability of the concept to fit uses from data organisation to object separation to providing new ways to move, Wesson argues that dimensionality gives a standardised mathematical (and particularly geometrical) way of sorting all the information and integrating it into the rest of the scientific enterprise in general, and into the interactions of basic properties in particular. In this, dimensions have become crucial to the scientific paradigms of many physicists; even if they are fabricated, they are “inventions whose geometrical usefulness for physics involves a well-judged use of the fundamental constants” (Wesson, p.4).

Although most scientists do not seem to dwell on, in print at least, the ontological status of dimensions there are occasional admissions that dimensions are interpreted only instrumentally, following Wesson’s analysis. For instance, Christopher Ray states that “when we think of multi-dimensional worlds, we regard dimension, not as a ‘physical property’, but as a ‘degree of freedom’, or as a ‘variable’ needed to describe a topological manifold” (Ray, p.82). Interpreting ‘dimension’ in non-physical terms and as a variable may put one in mind of the variables used in calculating the many-dimensional spaces of ‘the economic market’ or ‘the climate’, where the coordinates exist only in an abstract space and where the geometrical account of our three spatial dimensions no longer holds.

What physicists wish to do with the data (i.e. which property values they wish to calculate for certain phenomena), say, if they want to compute the rest mass of a macroscopic object or the quantum rest mass of a microscopic object, determines the dimensional scale used, which can mean that non-geometrical properties in one model of dimensions can be viewed geometrically, and thus more tractably, in a higher dimensional model. For instance, Wesson argues that non electro-magnetic “‘charges’ associated with particle physics…should be geometrized and then treated as coordinates in the matching *N*-dimensional manifold” (Wesson, p.11). The same approach to mathematical simplification is found in Randall, particularly as concerns strongly-interacting theories, which “are almost always impossible to interpret without an alternate, weakly interacting description…Only…[such a] theory has a simple enough formulation to use for computation" (Randall, p.450).

As may apply to scientific realism in general, few would like 'mathematical tractability to humans' to count as a reason for the universe to possess the number of dimensions it does, and so one should be cautious in separating any obvious uses of dimensionality for instrumental reasons from its uses in physical description. In the latter case, it makes sense to further specify what those higher-dimensional coordinates mean in physical terms. Wesson endorses this approach, arguing, for instance, that "we should have a physical identification of the extra coordinates, in order to understand the implications of their associated dimensions. In 5D, we have seen that the extra coordinate can profitably be related to rest mass" (Wesson, p.25). Although some theories have singled out non-geometrical (at least given our 3-dimensinoal conception) properties, much more analysis on why *those* properties have their own dimension and how exactly they work needs to be done.

The scientific focus on prediction also lends itself to instrumental interpretations of utility and convenience, and it can be very difficult to separate the instrumental components of a theory from the ontological claims when the subject matter is so far removed from observation and experience. For example, Hans Reichenbach described the interchangeability of different dimensional descriptions, taking the state of a static gas as an example, which can be described as n molecules in three-dimensional space or as one point in 'parameter' space with $3n$ dimensions. Likewise a diatomic gas molecule has 6 degrees of freedom even though the centre of mass for the entire molecule accounts for 3 degrees of freedom. Nerlich rejects this purported equivalence, arguing that "it is only mathematically (in a rather abstract way too) that the pictures are alike…the example does not begin to get off the ground as providing two 'competing' descriptions with a common core of basic factual ideas" (Nerlich, p.152).

But this is not obvious and physicists themselves may suffer from this confusion, easily altering their talk on dimensions for convenience or in the pursuit of some larger unifying scheme. Concepts are easily rearranged, and dimensions as "degrees of freedom may be removed by imposing initial conditions on the geometry, physical conditions on the matter, or conditions on a boundary" (Wesson, p.23). From geometrodynamics to more recent suggestions for simplifying descriptions, there have been suggestions supporting the merging of qualities used in dimensional analysis with the geometric qualities of traditional spatial language that might dictate an instrumental approach, but this move should not go unanalysed. There is room for both agnostics who do not think it matters *whether* dimensions are real (undoubtedly some mathematicians and physicists fall into this group), and those who think it *does* matter. For those that favour dimensional realism, there are additional theories to choose from concerning the possession of dimensional properties.

12.2 Dimensionality as a property of spacetime

Dimensionality is largely seen not as a property of objects but as a property of space, which is perhaps unsurprising given a scientific tradition dominated by implicit substantivalism. In this light, most seem to take dimensions as a *discoverable* property of space rather than as simply an instrument to reveal interesting relations between objects. At least in lower dimensions, many of the mathematical properties of particular dimensional spaces allow one to determine the nature of that space entirely from within its confines (assuming one can carry out the necessary measurements). Such geometrical properties "are not simply features of the way we have chosen to embed the surface in the surrounding space; they are intrinsic to the surface itself" (Davies p.102). For example, on the 2D surface of a sphere, the angles of a large triangle do not equal 180^0; and in a spherical 3D space, the surface area is found to be, in general, smaller than the Euclidean requirement of a $4\pi r^2$ proportionality to its radius (Davies p.102). Taking dimensions as real also certainly fits nicely into our descriptive story of causality and the more familiar space we inhabit, and gives space a structural component with which to engage matter (as we describe it doing in general relativity for example).

Under this assumption we find that the properties an object has can depend upon the space in which it is embedded, making such properties extrinsic according to traditional accounts. For instance, whether an object can be enantiomorphic or homomorphic seems to depend on the structure of space, or at the very least on the relation of other objects[88]. Properties like *being enantiomorphic*[89] lie toward the periphery of our significant metaphysical debates, however, prompting few to explore the impact of dimensionality. But this complacency is shifting, partly because physicists have become much more eager to

[88] For instance, Nerlich argues that "whether a hand or a knee is enantiomorphic or homomorphic depends on the nature of the space it is in. In particular, it depends on the dimensionality or the orientability, but in any case on some aspect of the overall connectedness or topology of the space" (Nerlich, p.37). Sklar agrees, but does not think that anything "in the dependence of congruity and incongruity on global facts about space, refutes the relationist approach to the metaphysics of space" (Sklar, p.234). Certainly the relationalist has recourse to laws as being a limiting element to permitted movements instead of dimensions (Dainton, p.230).

[89] This may be generalized as: "an asymmetrical n-dimensional object is enantiomorphic in a space of n dimensions, but not in a space of n + 1 dimensions" (Dainton, p.229).

embrace higher-dimensional theories and partly because we are uncertain of the constraints and nomic interactions of dimensionality. More physicists are exploring the possibility that very basic, even 'intrinsic' or essential object properties are a product of dimensional structure. Under some current models, an object's mass is determined by its dimensions while a highly energetic object's momentum depends on the inhabited dimensions' size and shape (Randall, p.354). A by-product of theses approaches (it certainly was not the reason for forming them) is the new role they give space; beyond acting as a container for things to exist and constraining their motions and relations, space now "directly controls the *properties* that material things possess and can possess" (Dainton, p.330). Even if these models turn out to be incorrect, they usefully bring to the fore the weaknesses and problems in our expectations and accounts of dimensionality.

Part of the effort thus far has been to understand how the mathematic and geometric models physically manifest and what higher-dimensional geometries mean in lower-dimensional spaces. For instance, theorists in this field commonly think that "the relationship between mass and momentum imposed by special relativity tells us that extra-dimensional momentum would be seen in the four-dimensional world as mass" (Randall, p.353). We are generally quite biased (and understandably so) toward a three-dimensional conception of position, which is a quality that is generally not considered intrinsic. If we were to examine position at a higher dimension, however, we might discover that many of the characteristics we are traditionally inclined to view as intrinsic (mass, charge etc.) appear as no more than a coordinate of position in a more complex space. According to one model, one of the "consequences of warped geometry is that size, mass and even time depend on position along the fifth dimension" (Randall, p.387).

If position in two or three dimensions does not count as an intrinsic property, why should position along a fourth or fifth dimension count? Seriously addressing the implications of our dimensional theories has the potential to radically alter many metaphysical debates, particularly but not only if higher-dimensional theories are experimentally verified. If such higher-dimensional "geometry determines fundamental physical attributes like particle masses and charges that we observe in the usual three large space dimensions of common experience" (Greene, Elegant Universe, p.206), then there seems reason to believe that viewable 3-dimensional geometry would similarly determine lower-dimensional attributes and give us a better understanding of them.

We need not look only at higher dimensional models, however, as this concern for dimensionally-dependent properties can be seen in current dimensional morphing techniques as well. In the thin epitaxial layers of semi-conducting films, electrons can be confined to a width of 50 Å from which “the world looks distinctly two-dimensional. And indeed new properties emerge as a consequence. If an electron finds itself…confined to the carbon chain of a polymer, the world is now one-dimensional, and even stranger properties, such as superconductivity may emerge” (Ridley, p.46). Of course, such confinement is not *strictly* engaging two or one dimensions—the electron still inhabits a 3-dimensional world—but the approximation’s change in behaviour can be telling. It is from such accounts that we make predictions of the way dimensionality alters properties. For example, “if a wave or particle is confined to a tiny, tiny space, where its position is thus highly constrained, it will have tremendous momentum and a correspondingly high mass. Conversely, if the extra dimensions are large, the wave or particle will have more room to move in and correspondingly less momentum, and will therefore be lighter” (Yau, p.284).

It seems reasonable to suppose that the behavioural effects of any objects traversing independent pathways (different dimensions) will become altered relative to lower or higher spatial regions and could give rise to seemingly disparate perceived phenomena that manifest according to, say, our rules for ‘momentum’, even if they follows our rules for ‘position’ in higher dimensional terms. These sorts of analogies do not produce uniform confidence, let alone guidance, however, and Callender’s caution about assuming the priority of constraints is well taken, particularly if we consider space to be topologically inhomogeneous. It is not too difficult to suppose that the universe might have inhomogeneous dimensionality, for instance, with at least apparent differences in the numbers of dimensions for different regions of space (Randall, p.444). Further, there may be singular regions of varying dimensionality that “appear as the limit of regions of increasingly sharp curvatures, like horns or cusps, or as sudden ‘holes’ in an otherwise relatively flat manifold; they may affect all geometrical quantities, or only some of them’ and they may have devastating effects on some physical process, but none at all on others” (Graves, p.228). Some balance of caution and hypothesising (particularly as concerns what laws or structures take priority) needs to be made explicit in any good physical theory to avoid assumptions getting smuggled in the back door or simply by ignoring dimensional implications.

Bearing in mind that frameworks like string theory hypothesise unproven entities and relations, we should nonetheless be able to locate telling areas of uncertainty in our handling of dimensionality. Perhaps we do not know exactly *how* dimensions shape properties, but it "appears that the dimensionality of the world plays a key part in determining the form of the laws of physics and in fashioning the roles played by the constants of Nature" (Barrow, p.337). Lacking the specific ways that dimensions shape properties, we might still be able to review some of the structural elements—like connectivity—that seem central to our understanding of the concept as well as exploring other attributions for dimensionality itself. For instance we might investigate whether our 'degrees of freedom and independent pathways' picture of dimensions gives us any notion of primacy for either the pathways or the objects. Additionally we might explore the possibility that the number of dimensions is no more absolute than time, or the 'right' perspective. In this, dimensionality might be a matter of how one cuts the 'hyperplanes' of spacetime—a suggestion that, again, will need more mathematical exploration to give it weight.

The philosophical interest in this area has generally revolved around the relationalist/ substantivalist debate, and although we should be cautious of adopting those arguments directly into this framework, reviewing analyses like Nerlich's on pathwise space could help inform and situate the discussion. For instance, he might be interpreted as giving the objects (or nodes) priority over the pathways: "I do claim that in all possible worlds, as we ordinarily envisage them in philosophy, there always is a path between two objects that do not touch each other" (Nerlich, p.42). Elsewhere such nodes include spacetime regions, but in any case it is these pathways that make up the space; "a space is just the union of pathwise connected regions (Nerlich, p.44).

Making sense of the primacy of pathways or their nodes/ objects in our theories and expectations could clarify our view on dimensions and their attribution. For instance, low energy processes in higher dimensions will not always be able to take advantage of the extra-dimensional pathways for movement, and thus may lack any distinguishing feature of the higher dimensional qualities of momentum or structure (Randall, p.355). This raises the possibility that dimensionality might not be simply a property of spacetime, but that it might in some way depend on the object and its other properties, for instance, its energy; after all, it was in response to a need for localising enough energy and independent movement that string theorists first posited higher dimensions[90].

[90] This move follows the basic assumption that more dimensions means more possible directions of motion, that is, "more dimensions means more vibrational patterns" (Greene, p.370) are possible.

12.3 Dimensionality as a property of objects

It may be that objects, and not space, bear the property of dimensionality, a possibility that would appeal to both the dispositional essentialist and the relationalist (though the substantivalist could account for it as well). Mathematical treatment of objects gives a ready model to this theory, whereby the number of dimensions is seen to rise with the number of objects; with more objects haphazardly moving through space "the complexity of the system goes up, as does the dimensionality" (Yau, p.4). The relationalist could try to account for dimensionality restrictions (e.g. incongruent counterparts, should they exist) by having the objects restricted to certain 'planes' of action by law or some as yet unknown aspect of the object.

A substantivalist could also accommodate objects bearing dimensional properties, whereby space—if a real substance—might a) be totally without such structure in this way, b) be infinitely dimensional, such that it alone cannot account for the restrictions on interaction/ movement for objects of varying dimensions, or c) have some dimensional structure with which certain fundamental entities may be able to engage. This latter option might mean that space derivatively acquires the dimension of whatever object currently inhabits it, or it might mean that objects and space in some other way collaborate to give the dimensional structure suggested by some theories. While these options do not exhaust the possibilities, it would be interesting to see if any mathematical formulism could support them, as well as more developed philosophical implications.

As mentioned, for the non-substantivalist a different story is likely to be told about dimensionality, attributing it to the objects themselves or to some governing law, which is not likely to be any easy mathematical feat, but the option is at least currently open. Bede Rundle, for instance, takes space to have a subservient role to objects:

> Not only is space dependent on matter for its existence, but others of its features may also flow from its dependence…Possession of [three-dimensionality] by objects is straightforward, but if we delineate a three-dimensional structure by tracing out appropriate lines between bodies, does this show that space itself has three dimensions? It tells us something about the dimensionality of objects which might occupy space, but by way of saying what 'Space is three-dimensional' *means*. Would space have more individuality if it were not true that any two objects in space were in

> the same space, if somehow there were no path from space s_1 to space s_2? But the spaces in question would still have to be identified in terms of the objects in them. It would be a matter of there being no way of linking up *objects* in the spaces which each identified (Rundle, p.218).

Beyond such intuitions, perhaps the strongest argument in favour of such a view is again parsimony; it is ontologically simpler to just carry on giving attributes to objects rather than hypothesising some vast and structurally complex thing (dimension) that modifies those attributes. Whether objects can bear certain relations to each other, take on certain extensions and shapes, or interact with other objects in certain ways may all simply depend upon the nature or disposition of the object itself. Given that objects and their behaviour seem to be the best and perhaps only guide to our understanding the entity called ‘space’, we only get a clue about different dimensions when some object exhibits certain behaviour. Simply embedding a lower dimensional object in a higher dimensional (or no dimensional) space need not mean the object can ‘take advantage’ of the new degrees of freedom.

A good deal more of the mathematics needs to be explored to really evaluate this possibility, however, as does a plausible enough mechanism to delimit the interactions of certain species of object. It may be that, like superstring theory, an explanation can be found in the manifestation of energy from fundamental entities whereby the permitted (for whatever reason) or most efficient vibrations need such-and-such number of non-overlapping (perhaps orthogonal) wavebands in which to move. For example, to get a jump rope to undulate 500 times per second, it might not be enough to produce waves in the ‘up-down’ direction requiring further ‘side-to-side’ undulations to dissipate the energy.

Our failure to detect higher dimensions raises the likelihood that if they do exist, they are very very small and spatially constituted. But it might be possible to translate this idea of ‘ubiquitous minute dimensions’ to ‘multidimensional movement in certain contexts’ such that entities might still move in higher dimensions wherever they need to (thus accounting for the ubiquitous aspect) and for only certain kinds of entities or interactions (thus accounting for both the minute dimensions and our inability to observe them). If such a physical theory cannot be formulated, then we have good reason to embrace space as the dimensional property bearer, and—if higher dimensions are proven to exist—we may have further reasons to adopt a realist stance towards space (which does not in itself force a dualistic or monistic substantivalism upon us).

The many interconnecting elements that will need to be parsed out in order to understand the assumptions, nuances and implications of dimensionality and dimensions are not easy to pull apart in a linear way, and no doubt advances in one area will demand a retuning of other areas. But such an interconnected and somewhat messy affair is in keeping with the more integrated and interdependent approach I have adopted in general, and will hopefully not be a detractor to initiating the enterprise. Undeniably, dimensions give a powerful tool with which to divide and explain the universe, but it is important to know whether that is all they do, in the same way that determining whether the ether was merely a tool was important.

For spatial realists (substantivalists and supersubstantivalists included), dimensions will presumably afford tempting structures that critically organise information and perhaps collaborate in the formation of properties and laws. Substantivalists are also free to attribute dimensionality to objects rather than space—nothing in their theory prevents them from doing so—though I imagine it will make the most sense (as so many discussions of 'handedness' demonstrate) to assign dimensionality to space first and foremost. For the staunch relationalist,on the other hand, dimensions may be loose talk that a deeper understanding of laws or matter could reshape into some palatable aspect of the object-rich world we inhabit. More moderate relationalists—who accept space but as a *non-fundamental substance*—or dense relationalists who may use talk of 'space' to signify particular fields—could also entertain the notion of dimensionality arising not simply through individual objects; dimensions could be a property of an emergent or field-constituted space. In any case, the exploration of dimensions and dimensionality offers a significant metaphysical landscape, as well as a study in mathematical interpretation that, I argue, is overdue for analysis.

12.4 Future Programme

I have reviewed some of the most significant issues for 'space', including concerns that it does not guarantee separation, suggestions for distinguishing real from abstract space, and a look at its possible dimensional structure. My primary goal in the last three chapters was to convince the reader that dimensionality is a rich metaphysical concept in need of study. Simply joining the physicists in searching for the magic number of dimensions misses all the foundational work that lets us know what we are talking about. Suppose I tell you that "Boggles are everywhere—they are key to the structure of the universe! Sometimes 7

Boggles creates the same world as 16 Boggles, but it can depend on other issues like Troggles". Assuming you care to make sense of what I said, you will enquire after these curious Boggles and usefully fit them alongside or under other relevant and important categories of understanding that best explain their behaviour and roles. If this is an obvious response then it is all the more puzzling that philosophers have been so slow to address it in terms of dimensionality.

Perhaps the main reason for this reticence is a belief that such pursuits are properly in the physicist's purview rather than in the philosopher's. I think there is a need for both; physicists are often in the business of interpreting mathematical formulae and models into physical phenomena, tying a collection of symbols to the relevant proportions expressed in events of a certain type (i.e. I can determine the momentum of an object from collecting the proportionally related variables of mass and velocity). But physicists do not always get it right; they can fall prey to confirmation bias; or they can become so far-removed from familiar phenomena that they have no clear conception of the physical manifestation of some mathematical terms or whether every term has such a manifestation (and is not simply an instrumental modifier). Indeed, there is a concern that once we move beyond a certain familiarity with the phenomena we study, we will always be lost in connecting them to our concepts of understanding. As Bohr aptly noted: "however far the phenomena transcend the scope of classical physical explanation, the account of all evidence must be expressed in classical terms…observations must be expressed in unambiguous language with suitable application of the terminology of classical physics" (Bohr, p.209). This is a real concern that we may not always work our way around, but there are other cases—like those of dimensions—that are not yet proven to be beyond our grasp.

Philosophers can be useful in such cases, clarifying the commitments, pointing out weaknesses and helping to develop structures for analysis. This activity may also be of use to philosophers in other disciplines. For instance, in discussions that grapple with mind-body dualism, the nature of 'emergence' or even the analysis of dimensional semantics, we can review the reasons why some properties/aspects/qualities are seen as independent variables. There is always an underlying framework that adopts certain assumptions that in turn helps to distinguish what counts as independent (e.g. our 3-dimensional assumption that position is extrinsic). These frameworks, in addition to many of their precepts, should be reviewed to better determine their appropriateness in light of modern physics.

Future work in this area should include at least the following. 1) It will be important to sort out what our expectations are for dimensions as well as exploring the mathematical formalism behind those theories; 2) following that foundation, or perhaps concurrently, we need to develop what is required for a clear realist framework; 3) we need to scout out the possibilities for dimensional property bearers (whether dimensions can be or are possessed by objects as well as by space) and dimensions as an organising principle (that can explain interactions and informational ordering—presumably in a geometrically accessible model); 4) Callender's concern with primacy will also be important to address—ideally through experiment—so that there is an established method for adopting certain laws or behaviours as more fundamental than others when examining different dimensional models.

Further, 5) we should better elucidate the implications and nature of the types of equivalences encountered. This will likely make us re-examine 'properties', or 'values', as having the same underlying cause with different manifestations from different perspectives. In this it may not be that different from what was once seen as electricity under one interaction and magnetism under another, and which is now seen as electromagnetism. Similarly, it may be that there is no fact of the matter about the number of dimensions, in much the same way that there is no preferred reference frame, no privileged way to slice spacetime. As should be clear, there is a good deal of work to do concerning dimensionality, particularly as regards our current physical theories. The strangely minimal engagement of philosophers and even physicists with the exact nature, expectations for, and interpretation of 'dimension' does both disciplines a disservice as the concept is surely a worthy topic that goes to the heart of the metaphysical programme.

Conclusion

In this dissertation, I have argued that we should both re-evaluate the presence of classical ontological models in metaphysics and readily engage science with philosophy. The particular union of physics and metaphysics discussed offers reasons for overturning the classical notion of an object, exploring a singular fundamental ontology, and for addressing the puzzles of physical space and dimension. In Part I, I criticised the pre-theoretical, 'classical', concept of an object, describing the context and central definition of an intrinsic property as a property that does not depend (even partly) on anything else. I then outlined attendant philosophical concerns such as the circularity of duplication, the irreconcilability of intuitions, and the assumption that hypothetical situations more accurately reveal the object *in itself* than in situ.

I reviewed physical examples that point to both interdependent and indeterminate properties and boundaries, looking at difficulties of classification in terms of reference frames, virtual particles and the pervasive dependence of properties in modern physical models. Traditional intrinsic properties like mass are, I argued, *extrinsic* by definition—further, I found the extrinsic grounding of mass indicative of a larger failure of intrinsic properties, making the intrinsic/ extrinsic distinction lose its utility. I then explored some of the ways we might deal with the issue, ultimately rejecting the distinction in favour of finding models that could do more work.

In Part II, I continued exploring the classical conception of an object and its interaction with its environment, this time largely in terms of the substantival model. It was put in context with its main rivals relationalism and supersubstantivalism, both of which were lauded for their parsimonious unification though I focused on the latter (SS). I argued that there are many benefits of SS, though they are not, I think, as overwhelming as (Schaffer 2009) makes them out to be. Returning to substantivalism, although noting that the central complaint against it is generally the 'hole argument', I was more interested here in substantivalism's other baggage and whether it was the best model for various challenging physical phenomena. To this end, I argued that the substantival model raises more questions than answers when it comes to describing space in terms of fields, expansion, emergence, or when empty. I also explored substantivalism's problematic 'occupation relation' as well as persisting concerns with the reification of points in some substantival models. I found the interaction between dual substances as mysterious as it was in the Cartesian model and argued for developing monistic ontologies; while supersubstantivalism is susceptible to the geometrisation concerns of substantivalism, there is certainly room for other singular ontological theories, dense relationalist or otherwise that should be explored.

In Part III, I searched for a clearer idea of what space *is*, using phenomena like entanglement, tunnelling and the double slit experiment to reveal the non-separability of space; i.e. that spatial separation does not guarantee causal separation. I also explored what we mean by real physical space in epistemic and constitutive terms, that is, as an integral means of experiencing the world and as a host to certain fundamental properties. In this, I surveyed several seemingly abstract spaces of physics and suggested that some of the loosely defined criteria we use to distinguish real physical space needs to be tightened. I also explored what we are to make of one of the most common spatial characteristics: dimensions.

Because there is so little literature on this subject, my aim here was to raise awareness, scouting out the main issues, characteristics and themes. I first canvassed some of the confusion expressed by those who work most intimately with dimensions, and sketched some of the main components of possible definitions. I reviewed some of the terms' more significant uses and looked at the main implications of taking a realist or instrumentalist stance towards dimensions, including whether they are properties of objects rather than space. Much more work by philosophers and physicists needs to be done before conclusions can be drawn, however, so here I have contented myself with making the case for such an enquiry.

There are lots of case studies in this work that point down many tangential, but promising, byways—I may have strayed down a few myself—but there are also important themes that bind together this research; there are explicit themes of ontological status, of classical and modern approaches to metaphysics, and of exotic worlds of matter and space. There are also implicit themes of an interdisciplinary methodology that keeps metaphysics scientifically up to date. Allowing myself a brief indulgence: I think there is a critical role for reflective analysis in a time when scientists are not only in positions of great influence (which is not all that new), but often publicly disparage philosophy. Indeed, it's hard to look at these disciplines without noting the asymmetric regard that each generally feels towards the other.

Philosophy, in general, respects the sciences and welcomes their essential exploration of the world, but the admiration is rarely reciprocal. Scientists have a bad habit of dismissing philosophy—and often much of the humanities—as unimportant, but in this they fundamentally misunderstand their role and the real need for the reflection, memory and depth the humanities provide. I do not believe there will ever come a time when we do not need to connect scientific phenomena with the rest of our knowledge, and there will *never* be a time when science is done without a philosophy, as Dennett so aptly notes:

> scientists sometimes deceive themselves into thinking that philosophical ideas are only, at best, decorations or parasitic commentaries on the hard, objective triumphs of science, and that they themselves are immune to the confusions that philosophers devote their lives to dissolving. But there is no such thing as philosophy-free science; there is only science whose philosophical baggage is taken on board without examination (Dennett 1995, p.21).

To avoid the criticisms of ignorant or unsympathetic scientists, philosophers need to engage with modern science, lend their hands to organisation and interpretation of material, point to overlooked or new areas of research and, critically, to check the assumptions that scientists make in fruitful and informed ways. I do not mean to collapse metaphysics into philosophy of physics or even into philosophy of science more generally. Rather, I think that there is a useful and larger space for examining and integrating the phenomena, categories and processes of scientific enquiry with *our* ways of understanding the world. Like Bohr's reference to the quantum and classical divide or Kant's view of the inalienable restrictions human perception imposes, we seem unable—in principle—to remove ourselves from the pursuit of much objective analysis and explanation. However, metaphysics offers a powerful means of integration that bridges old terms, structures and theories with new ones. I believe my research is very much in this spirit.

In partnership with physics, I have sought to dismantle the comfortable and clear distinctions between object and the container space, endorsing both a new interactive and interdependent model for analysis, as well as a closer dialogue with physics in general. These commitments may lead us to abandon old distinctions (e.g. the intrinsic/ extrinsic distinction, substantivalism), embrace new ones (non-separability, supersubstantivalism) and open new areas to metaphysical review (dimensions). There is a very real analogy with bridge building here, as philosophy in general and metaphysics in particular, try to stay relevant in a changing academic environment: it is far less useful to wait until *after* all bridges are built to analyse them for faults, and better to analyse before or as you go—even (and especially) if it is a bridge to nowhere.

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