A Theory of the Universe from Contemporary Physics:

Evaluating Smolin's Argument for the Elimination of 'Ideal Elements'

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Abstract

I explore Leibnizian themes in the theoretical physicist's pursuit of a quantum cosmology by examining Smolin's program based on the elimination of ideal elements.[1] These constructs are formal mathematical structures of a physical theory that require for their interpretation the existence of objects external to the system treated by the theory. After introducing some necessary background information, I discuss the particulars of Smolin's definition of ideal elements and analyze his motivations and arguments for the elimination of ideal elements. I then survey and assess his two specific proposals for the construction of a quantum cosmology. The former stems from the canonical approach to the development of a quantum theory of gravity; the latter consists of a series of hypotheses framing a speculative fundamental theory of the universe. Finally, I consider the explicit links and debts of Smolin's program to Leibniz's philosophy.

[1] See [41].

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1 Quantum Gravity, Quantum Cosmology, and All That

1.1 Leibnizian Themes at the Frontier of Physics

In the ongoing quest for a quantum theory of gravity, Gottfried Wilhelm Leibniz's philosophy finds a modern revival. This circumstance may surprise the stranger to such pursuits—21st century physicists attempting to unify general relativity with quantum mechanics through 17th century thought—but the practitioner perceives good reason to peer backwards. Today we most famously remember Leibniz for his row with Sir Isaac Newton: the two brilliant men disputed not only the attribution of credit for inventing calculus, but also the true nature of motion. The latter disagreement, subsequently coined the absolute–relative debate, draws Leibniz's philosophy into contemporary physics. For, this puzzle sits at the heart of conceptual and technical efforts to construct a quantum theory of gravity.

The Leibnizian approach to classical and quantum gravity is most commonly associated with the work of Julian Barbour.[2] In the past thirty years he has pioneered the application of Leibnizian and Machian ideas to the foundations of physics. His research has helped to elucidate the Machian bases of both classical mechanics and general relativity and to establish novel approaches to understanding quantum gravity. Instead of exploring Leibnizian themes directly through Barbour's work, I have elected to examine the paper *Space and Time in the Quantum Universe* by Lee Smolin, a former collaborator of Barbour. Smolin confronts the problem of constructing a physical theory of a closed system from contemporary physics. Drawing on the Leibnizian viewpoint, he develops a strategy for attacking this problem based on his concept of ideal element. He then presents two proposals outlining explicit solutions to the problem. After presenting some introductory material in the following three subsections, including an overview of Smolin's article, I begin my analysis of this particular Leibnizian approach in the second section.

1.2 Theoretical Physicist's Wish List

A quantum theory of gravity and a quantum theory of the entire universe easily top my list of the most desirable goals of contemporary physics.[3] After these two potential accomplishments of human ingenuity and intellect, my rankings becomes murkier. The following issues occupy the next five places in no particularly definite order: a resolution to the measurement problem of quantum theory, an explanation of the arrow of time, a grand unified theory of the electromagnetic, weak nuclear, and strong nuclear forces, a prediction of the universe's particle content and natural constants, and a solution to the cosmological constant problem. All of these issues clearly do not exist in isolation; they interconnect one with another, a hopeful indication of the unity of physics.

Allow me to return to the top two places on my list. These two pursuits will concern us throughout my essay, so I should further introduce them now. The quantum theory of gravity designates the hypothetical unification of gen-

[2]See [1, 2, 3, 4, 6, 7, 8, 10].

[3]The extent to which these two pursuits coincide remains undetermined.

eral relativity with quantum mechanics. These latter two theories form the basis of our most fundamental understanding of the physical world. Both theories have withstood extensive experimental tests, yet they have never been probed in regimes where the two theories' respective effects appreciably interact. Both theories claim universality of application, yet they differ markedly and incompatibly in their modes of description. Physicists thus think that we must reconcile the two theories in some appropriate unification. Besides the two theories' experimental successes, there are several reasons to believe that we must retain aspects of both general relativity and quantum mechanics in a more fundamental theory. Foremost of these is the fact that general relativity and quantum mechanics describe complementary aspects of the physical world. General relativity represents our deepest understanding of space, time, and gravitation; quantum mechanics represents our deepest understanding of matter and its (nongravitational) interactions. General relativity employs an effective, coarse-grained description of matter; quantum mechanics employs an outmoded, simplified description of spacetime. Where the middle ground lies, however, still remains a mystery.[4]

A quantum cosmology is a theory of a closed system that incorporates quantum mechanics in some appropriate manner. Physicists tacitly assume that a closed system refers to the universe because "the smallest closed system [that] we observe appears to be astronomically large and is generally known as the [u]niverse."[5] The theoretical pursuits of quantum gravity and of quantum cosmology are often linked. Some physicists contend that the former is tantamount to the latter, and some physicists contend that the latter is tantamount to the former. In any case, as general relativity forms the basis of our best descriptions of both gravitation and cosmology, the attempt to bring quantum mechanics to this theory appears to necessarily intertwine the two aforementioned pursuits. Despite decades of determined effort, we have yet to develop satisfactory theories of quantum gravity and of quantum cosmology. There exist a myriad of reasons for this situation, conceptual and technical. In his article Smolin identifies a particular cause and builds a novel approach to quantum cosmology upon it. As Smolin argues and as most physicists in this field maintain, two recalcitrant problems stand at the heart of quantum gravity.

1.3 Two Most Popular Physics Problems for Philosophers

1.3.1 The Absolute–Relative Debate

Our first problem—the absolute–relative debate over the nature of motion—has a history surpassing three centuries: we typically trace its origins to the dispute between Newton and Leibniz sparked by the publication of the former's theory of dynamics in the 1687 *Philosophiae Naturalis Principia Mathematica*. Newton promoted the notions of absolute space and absolute time as the true stage on which dynamics plays out. Leibniz countered, arguing that all motion is relative: "space being an order of coexistence as time is an order of successions."[6] Although Leibniz might have possessed the epistemological upper hand, Newton definitely had ontological superiority. For, as various physicists and philosophers

[4]See [15] for a good philosopher's introduction to quantum gravity.
[5][34], 2885.
[6]Quoted in [41] on page 228.

have remarked, the absolute–relative debate is decided by dynamical theory.[7] Newton had a powerfully predictive theory; Leibniz had an eminently attractive philosophy.

Absolute space and time came under fire from various sources—most notably, George Berkeley and Ernst Mach—through the remainder of the prerelativistic period. As none of these critics could produce a relational dynamics to challenge Newton's, the latter theory remained ascendant. Mach did, however, make a lasting contribution. He hypothesized that there might be an alternative, dynamical explanation for the appearance of absolute acceleration in classical mechanics: distant matter in the universe provides an effective frame of reference with respect to which acceleration actually occurs. He also hypothesized that the phenomenon of inertia arises from the interaction of local with distant matter. Although Mach fell short of constructing a theory embodying this idea, he gave impetus to the relationalist[8] program by elucidating a dynamical mechanism that had the potential to replace absolute space. Einstein, who coined the phrase Mach's principle for the above conjecture, cited its influence in the development of general relativity. Barbour, who later distinguished two Mach's principles, employed these ideas to elucidate the relational underpinnings of general relativity.

The development of special relativity theory revived the debate: with a new dynamics physicists and philosophers could weigh the theory's import for the nature of motion. Despite its suggestive name, special relativity sided with the absolutists. The theory's inertial frames serve much the same function as did Newton's absolute space and time; moreover, Minkowski spacetime—though a significant advance for physics—forms a fixed background.

With the advent of general relativity theory, the stage for the contemporary absolute–relative debate was largely set. General relativity incorporates several key features that complicate the dispute. Most importantly, the theory uses a dynamical spacetime metric, which evolves in intimate symbiosis with matter and energy according to the Einstein field equations. Thus, unlike in Newtonian mechanics and special relativity, the spacetime of general relativity is not fixed: it responds to and is partially determined by its matter and energy content. Our ability to differentiate spacetime from matter-energy is blurred. Secondarily, the spacetime metric is also isomorphic under arbitrary diffeomorphisms: we can recoordinatize spacetime in an infinite number of ways, all the while maintaining the physical content encoded in the metric and matter fields.[9] Needless to say, there remains controversy regarding general relativity's import for the absolute–relative debate.[10] In the contemporary philosophical literature these two positions have morphed into substantivalism and relationalism,

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[7]Barbour writes: "[A] distinction between [Newton's] absolute concepts and Leibniz's relational concepts becomes meaningful only at the level of dynamical theories of motion . . . The argument therefore hinges on the ability of rival camps to formulate dynamical laws of motion" ([1], 251). Ian Hacking writes: "There can be no determination of spatial relations without a study of the laws of nature attributed to objects in space" ([30], 250).

[8]I employ the adjective 'relationalist' rather than 'relativist' to avoid confusion with the latter's modern usage, denoting a physicist who studies relativity theory. As we shall see momentarily, 'relational' has replaced 'relative' in the contemporary debate.

[9]This so-called diffeomorphism invariance is an integral part of Einstein's famous hole argument.

[10]Some philosophers even contend that the debate is no longer viable. Others disagree. See [38] and [32], respectively.

respectively. Essentially, the substantivalist affirms that space or spacetime "exists independently of all material entities, consequently possessing certain intrinsic characteristics."[11] The relationalist denies this claim, maintaining that "spatiotemporal relations reduce completely to the relations amongst material entities."[12]

1982 marked a new high point for relationalism. That year Barbour and Bruno Bertotti published a relational reduction of Newtonian mechanics and elucidated the Machian basis of general relativity.[13] Although this work has not received the attention that it deserves, these results are reasonably well-known to researchers in the quantum gravity community. As we shall see, Smolin draws heavily on Barbour-Bertotti theory.[14]

1.3.2 The Measurement Problem

Our second problem—the measurement problem of quantum theory—has a comparatively short history: arising with the development of quantum mechanics in the latter 1920s, this puzzle rapidly became the fledgling theory's central conceptual quandary. The measurement problem concerns the evident incompatibility of the dynamics of a quantum-mechanical system in two situations: when the system evolves undisturbed and when the system is measured. The former dynamics obey the deterministic Schrödinger equation, completely following the theory's mathematical formalism. The latter dynamics appear to involve an instantaneous reduction of the wavefunction, crucially violating the theory's explicit predictions. Although these two forms of dynamics can be reconciled sufficiently to perform experimental tests and to exploit novel features of quantum theory, there remains the incompatibility of the two modes of evolution. The question of what actually happens when we measure remains baffling, elusive, open.

The measurement problem has provoked the proposal of an ever-increasing number of potential solutions. These solutions typically fall into one of two categories: novel interpretations of quantum theory intended to dissolve its difficulties, or subtle modifications of quantum theory intended to harmonize its two forms of dynamics. Each explanation has its ardent advocates, but most physicists still view the measurement problem as unresolved. Some physicists—Smolin included—advance the position that the measurement problem has no solution as posed. This perspective's motivations will prove of interest in ensuing sections.

1.4 *Space and Time in the Quantum Universe* in a Nutshell

Smolin addresses the problem of constructing a physical theory of a closed system from the perspective of contemporary physics. He begins by locating this task's conceptual and technical difficulties in the presence of ideal elements in our current physical theories. These constructs are formal elements of a theory's mathematical structure the interpretation of which requires the existence

[11] [18], 2.
[12] [18], 2. See [20] for a comprehensive discussion.
[13] See [8]. For philosophical commentary see [14, 36, 18].
[14] See the first appendix for a brief discussion of classical Barbour-Bertotti theory.

of objects external to the system described by the theory. Smolin illustrates his definition with examples from classical mechanics—inertial frames and absolute time—and from general relativity—cosmological symmetry assumptions. He then extensively discusses ideal elements in quantum mechanics. With this central concept firmly established, Smolin argues for the elimination of ideal elements from physical theory as the key to quantum cosmology. Drawing on Leibniz's principle of sufficient reason, he demonstrates why ideal elements necessitate externals for their interpretation and why ideal elements have no place in quantum cosmology.

This critical introductory work complete, Smolin turns to the constructive task at hand: building a theory of the universe on the pillars of general relativity and quantum mechanics. Supposing first that the canonical approach to quantum gravity holds promise, he drafts three criteria for an acceptable measurement theory of quantum cosmology. In particular, he maintains the necessity of finding an intrinsic time variable—a function on the theory's phase space that mimics the role of a time coordinate—for this approach's success. As an instructive example Smolin treats the quantization of prerelativistic Barbour-Bertotti theory. Unable to locate an intrinsic time, however, he cannot interpret this simplified quantum cosmology along the lines of his sketched measurement theory. Acknowledging the failure of all attempts to apply the intrinsic time program, Smolin proffers the substantial modification of quantum theory as the next alternative. To this end he presents a series of ten proposals for a speculative quantum cosmology devoid of ideal elements. To illustrate several of his ideas—especially his dynamical principle of maximal variety—Smolin considers graph-theoretic models as rudimentary solutions to his conjectured theory.

Smolin covers a lot of territory—from the absolute–relative debate through the interpretation of quantum theory to Dirac's large number hypothesis and the cosmological constant problem—in his engaging article; despite this breadth the paper is solidly unified by its primary aim—treating the problem of constructing a physical theory of a closed system through Leibnizian philosophy. Moreover, in bringing together these seemingly disparate foundational puzzles of modern physics, Smolin fosters a sense of unity in the natural world viewed through a Leibnizian lens.

My enthusiasm for Smolin's work aside, I believe that, while there is much to commend, there is also much to critique. In evaluating his article I do not touch on every topic that he discusses; instead, I concentrate on Leibnizian themes in quantum cosmology. I turn to Smolin's discussion of ideal elements in §2. First I examine his definition of ideal elements (§2.1) and consider his motivation to frame the problem of quantum cosmology with this construct (§2.2). As Smolin defines ideal elements, they differ little from theoretical structures that the relationalist would deem substantival; nevertheless, the definition allows him to make an insightful connection between the absolute–relative debate and the measurement problem. Then I analyze his two principal arguments from the principle of sufficient reason: for the necessity of extrinsic objects in the physical interpretation of ideal elements (§2.3) and for the elimination of ideal elements from physical theory (§2.4) These conclusions rely heavily on the principle of sufficient reason's deductive power; they also raise questions regarding the feasibility of Smolin's program. In §3 I address Smolin's two approaches to quantum cosmology: the first substantially maintaining quantum theory (§3.1), the second significantly modifying quantum theory (§3.2). The former approach, in addition to suffering from a lack of technical support, falls prey to Smolin's own argument against the inclusion of ideal elements. The latter approach, in addition to suffering from a lack of technical development, requires the rethinking of several of its key components.[15] Finally, in §4 I scrutinize the links and debts of Smolin's project to Leibniz's philosophy and Barbour's thought, commenting specifically on the former's use of the principle of sufficient reason (§4.1), maximal variety proposal (§4.2), and connections to relationalism (§4.3). I conclude that, except for a few notable insights, Smolin's work is largely derivative; furthermore, I argue that he is unjustified in his primary deviation from Leibniz's and Barbour's thought, namely, the retention of time as a fundamental notion.

2 On Ideal Elements

2.1 Definition

Smolin defines the ideal elements of a physical theory as

> absolute or background structures that are contingent, in the sense that they may be altered without altering the basic character of the theory, play a role in the dynamical equations of the theory, and are not themselves determined by solving any dynamical equations.[16]

He expounds further upon the first and third conditions.

> By contingent I mean that [the element] reflects an arbitrary choice, and that a different choice could have been made without altering the basic mathematical structure of the theory. By nondynamical I mean that the choice that is made is not arrived at by solving any dynamical equations, and cannot be influenced by the state of the dynamical degrees of freedom.[17]

Smolin illustrates his definition with examples of ideal elements in classical mechanics, general relativity, and quantum mechanics. Instead of analyzing how strictly these examples conform to the general definition—leaving evaluation of specific instances of ideal elements to necessary moments in my ensuing discussion—I scrutinize the concept of ideal element.

Smolin's definition is reasonably clear—he certainly conveys an intuitive sense for the concept—and his examples strengthen our grasp. Several avenues of inquiry and clarification nevertheless present themselves. First I more closely examine his three conditions in an attempt to refine his meaning. Next I reflect on his choice of the term 'ideal element'. Finally I compare Smolin's ideal elements to Leibniz's relational quantities and Barbour's uniform background structures.

To further elucidate the above definition, we must determine the intended connotations of four key words: absolute, background, contingent, and dynamical. Undoubtedly, Smolin employs 'absolute' in the sense of Newton's absolute

[15] Admittedly, Smolin acknowledges the speculative and schematic nature of his second proposal.

[16] [41], 231.

[17] [41], 239.

space and absolute time:[18] fixed, unchanging, independent. He uses 'background' almost synonymously to 'absolute', to denote theoretical elements that merely set the stage or provide a backdrop. 'Contingent' does not here possess its usual philosophical meaning in opposition to necessary truth; rather, 'contingent' is virtually synonymous with 'arbitrary', yet fitting the prescribed circumstances of its role in the theory. Finally, Smolin employs 'dynamical' in its generalized modern sense to refer to that which evolves according to the framing equations of a physical theory.

Given this analysis of the definition's language, why does Smolin choose the terminology 'ideal element'? The usage of 'element' is transparent: each ideal element is a structural component of the theory's mathematical edifice.[19] In what sense are these elements ideal? The usual meaning of 'ideal' suggests that in some appropriate fashion ideal elements are idealizations—perfected replacements for imperfect structures. I contend that this is Smolin's intended connotation since his prescription for the elimination of ideal elements involves their replacement with intrinsic yet approximate dynamical analogues.

These clarifications are helpful, but I would like to broach a more interesting and significant issue for my purpose of exploring Leibnizian themes. Why does Smolin feel the need to introduce the new terminology of ideal elements? My answer continues into the next three subsections, cropping up occasionally in the essay's remainder as well. Here I respond by comparing Smolin's ideal elements to two related concepts—Leibniz's relational quantities and Barbour's uniform background structures.

When debating the nature of motion, we require standards of judgment for determining if a given dynamical theory favors substantivalism or relationalism. These standards depend on sundry factors including the theory's context within the larger realm of physics, the theory's domain of applicability, and the viewpoints of those selecting the criteria. A particular method for establishing such standards of judgment involves the prior identification of certain theoretical quantities as being relational. We then deem relational any dynamical theory that only invokes these identified quantities and substantival any dynamical theory that also invokes additional quantities. Since the relationalist position stems from Leibniz, I propose to call these elements Leibnizian relational quantities. The archetypal example theory is of course Newtonian mechanics. In this context the Leibnizian relational quantities are the Euclidean distances between pairs of point particles.[20]

Now, what is the relationship between Smolin's ideal elements and Leibnizian relational quantities? First of all, Smolin's use of the adjectives 'absolute' and 'background' to describe ideal elements suggests an immediate connection. Those elements that do not qualify as relational we label substantival or absolute.[21] Smolin requires additional characteristics of his ideal elements. Do Leibnizian relational quantities mirror these features? For concreteness I suggest that we first consider the example of the Euclidean distance between point

[18] He cites these two constructs as the archetypal ideal elements.

[19] Note that Smolin does not remark upon the identifiability or the independence of ideal elements. In practice the identification, separation, and subsequent elimination of an ideal element might prove more difficult than the definition suggests.

[20] The masses of point particles also enter the theory; although not relational, we are justified in assuming these data because the theory makes no attempt to explain the origin of mass.

[21] Note that we seek a disanalogy between ideal elements and relational quantities.

particles in classical mechanics. How does this relational quantity compare? This distance is not contingent but certainly dynamical; however, the Euclidean metric, by which this distance is measured, meets the criteria of an ideal element. We still consider these Euclidean distances to be relational quantities because, in the context of classical dynamics, the assumption of Euclidean geometrical relations is clearly justified. Generalizing from this example, I conclude that ideal elements appear to constitute substantival structures, the counterparts to Leibnizian relational quantities, except that they incorporate no notion of contextuality. As we shall see, this absence of context underlies a potential difficulty for Smolin's proposal for the elimination of ideal elements. I return to the relationship between Smolin's program based on ideal elements and the relationalist program in §4.3.

Barbour gives as "the minimal ontological principles of the relation[al]ist standpoint" the following statement: "the existence of things is established through perceived variety and abstract uniformity is nothing."[22] He thereby introduces the notion of a uniform background structure, a standard against which we supposedly express and measure the change of perceived variety.[23] In the case of dynamical theories, space and time (or spacetime) constitute the two primary uniform background structures. Since Smolin identifies space and time as the two archetypal ideal elements, we are naturally led to inquire into the relation of ideal elements to uniform background structures. Clearly, the latter are contingent and nondynamical: the type of uniformity with which we endow our structure is tunable, and once so tuned our structure serves as a fixed reference. Uniform background structures thus qualify as ideal elements,[24] but do all ideal elements qualify as uniform background structures? Of all the examples that Smolin cites, only two do not immediately strike me as uniform background structures: the inner product on the quantum-mechanical state space and the correspondence of quantum-mechanical operators with classical observables. With a bit of thought, we quickly realize that the inner product is a uniform background structure. It provides a standard by which to measure the norm of any state space element. The aforementioned correspondence, however, does not straightforwardly conform to the definition of a uniform background structure. This analysis suggests that the ideal element is a more general concept. We must not yet dismiss uniform background structures, though; they reenter the discussion in the next subsection and in §4.3.

2.2 Framing the Problem of Quantum Cosmology

Smolin frames the problem of constructing a physical theory of a closed system using my two popular physics problems for philosophers, the absolute–relative debate and the measurement problem. He contends that the problem of quantum cosmology is "the basic issue behind [not only] the criticisms of Newtonian mechanics by Leibniz, Berkeley, and Mach, [but also] the problem of the interpretation of quantum mechanics."[25] He asserts that "quantum cosmology remains a complete enigma precisely because we have not learned how to re-

[22] [1], 254.
[23] [1], 252.
[24] I have not forgotten the second criteria: as I stated just above, we use uniform background structures to coordinate variety.
[25] [41], 230.

solve these two [issues]; [t]hat is, we do not know how to construct a theory that could be interpreted as a theory of an entire universe."[26] Furthermore, the development of a quantum theory of gravity—a pursuit intimately intertwined with that of quantum cosmology—stands at the nexus between these two long-standing problems; presumably, quantum gravity will require the simultaneous resolution of both issues.

Having rooted two of the most foundational questions of contemporary physics in the problem of quantum cosmology, Smolin offers a diagnosis and solution through his concept of ideal elements. He contends that both the absolute–relative debate and the measurement problem arise from the presence of ideal elements in the respective theories that these issues plague. By eliminating ideal elements from dynamical theory, Smolin hopes to neutralize our difficulties in formulating a theory of the entire universe. When we have overcome our reliance on ideal elements, we will finally be in a position to resolve the absolute–relative debate and the measurement problem through quantum cosmology. Smolin clearly envisions this resolution vindicating relationalism: a theory devoid of ideal elements could not be substantival. Smolin does not possess so clear a vision for the measurement problem, a fact which underscores the different characters of these two foundational puzzles.

Smolin's linking of the absolute–relative debate with the measurement problem represents a novel insight into the foundations of physics. His move leads us to inquire just how closely related these two issues are. As I presented the absolute–relative debate in §1.3, the key question was 'Does spacetime exist independently of material entities, or do spatiotemporal relations reduce to the relations amongst material entities?'. Smolin's characterization of the debate is similar except that, in emphasizing the difficulties for developing a universal theory involved in answering 'no' and 'yes' to my two questions, he links his portrayal to the broader concept of ideal element. Barbour contends that "the question at the heart of the criticism of Newtonian dynamics made by Leibniz, Berkeley, and Mach concerns precisely the use of *any* uniform standard in dynamical theory."[27] This characterization is clearly more general than mine since it does not limit itself to the uniform standards of space and time. As we have seen, this characterization is also closely related to Smolin's. Though Barbour identifies the use of uniform standards as the debate's crucial issue, he certainly realizes the relevance of treating the universe in its entirety.

Superficially at least, the measurement problem possesses quite a different character from that of the absolute–relative debate. Depending on how one conceives of the problem, it is an issue of either quantum theory's interpretation, quantum theory's incompleteness, or, *à la* Smolin, quantum theory's inapplicability to the entire universe. Interestingly, each of these aspects finds a resonance in the absolute–relative debate. First, the determination of a dynamical theory's status—substantival or relational—is not unequivocal: it depends on the interpretation of these two positions with respect to that theory. Second, a dynamical theory might well appear substantival or relational because it does not fully capture the intricacies of the world. A deeper understanding would reveal the world's relational or substantival character, respectively. Third, by failing to account for interactions with distant sectors of the universe, a dynamical theory

[26] [41], 231.
[27] [1], 252.

can appear substantival when it is in fact relational. Barbour-Bertotti theory demonstrates how a universally relational theory gives a substantival impression locally.[28]

The relation of the absolute–relative debate to the measurement problem thus depends on the lens through which we examine these two issues. Is one of these aspects most significant? Smolin clearly believes that the last is of critical concern for our pursuit of more fundamental physical theories. Before concluding this subsection, I would like to indicate one further such perspective. Consider the following three facts. Quantum theory imports unadulterated the kinematic structure of absolute space and time; the measurement problem is often claimed to arise from our need to reference a classical realm; all of the ideal elements of quantum mechanics that Smolin discusses ultimately refer to classical concepts. I now inquire: to what extent might the measurement problem stem directly from the reliance of quantum mechanics on classical concepts?[29] I do not pursue these thoughts further, but I believe them of sufficient interest to be mooted.

2.3 Argument for Externality

The frame for quantum cosmology that Smolin erects stands upon two foundational conclusions about the status of ideal elements in physical theory. First, he draws an important implication from the presence of ideal elements: the interpretation of an ideal element requires the existence of an object external to the system treated by the theory. Second, he employs this entailment to motivate the key step to constructing a quantum cosmology: the elimination of ideal elements from physical theory by replacement with dynamical analogues. To substantiate these claims, Smolin presents arguments for each based upon the principle of sufficient reason. I consider the first claim now; I treat his argument for elimination in the next subsection.

Smolin's argument for the necessity of externals in the interpretation of ideal elements proceeds as follows. He states three premises.

> *First Premise* The ideal element is present because it is necessary to explain something in the internal or local dynamics of the system under study.[30]
>
> *Second Premise* The theory that incorporates that ideal element may be assumed to be complete in the sense that once the ideal element has been specified, the internal dynamics is completely determined and produces predictions that agree with experiment.[31]
>
> *Third Premise* If Leibniz's argument impells us to replace that ideal element with a dynamical entity, that entity cannot be one of the dynamical degrees of freedom of the intrinsic system because that dynamics has already been completely specified.[32]

[28] See the first appendix.
[29] We might even wonder if the measurement problem results from the absolute–relative debate.
[30] [41], 246.
[31] [41], 246.
[32] [41], 246.

He draws this conclusion.

> *Conclusion* Hence, it must be something that is outside of the system under study.[33]

The first premise merely restates the function that an ideal elements performs in a dynamical theory. The second premise is a sound assumption: the ideal element has indeed been constructed to complete the theory in this predictive sense.[34] The third premise is a conditional statement that will prove true if the condition—"Leibniz's argument impells us to replace that ideal element with a dynamical entity"—is justified. To what does "Leibniz's argument" refer? Smolin here invokes Leibniz's principle of sufficient reason, which demands that there be a sufficient reason for any circumstance to exist or any event to occur in a certain manner.[35] Since an ideal element is contingent—it involves an arbitrariness of choice—its presence conflicts with the principle of sufficient reason. To satisfy Leibniz's principle, we must modify our theory so that it no longer contains ideal elements. Each ideal element, however, serves a necessary role in the theory's dynamics and interpretation; therefore, we cannot remove the ideal element without rendering the theory impotent and its interpretation incoherent. Aside from inventing a wholly new theory, our only option is to construct within the theory a dynamical analogue for the ideal element. This is essentially Smolin's argument for the elimination of ideal elements as we shall see in the next subsection. The dependence on the principle of sufficient reason is thus laid bare. Provided that we accept this consequence of Leibniz's central tenet, Smolin's argument succeeds. Moreover, the argument demonstrates the potential difficulty for quantum cosmology that ideal elements pose. The elimination of ideal elements becomes a necessary, but not sufficient, condition of the quest for quantum cosmology.[36]

2.4 Argument for Elimination

Smolin identifies the elimination of ideal elements from physical theory as both key and hurdle to constructing a quantum cosmology. As I discussed in the previous two subsections, he attempts to motivate this point of view by two means: insights into the resolution of foundational problems in physics and argument for the necessity of external objects in interpreting ideal elements. Motivations, especially when compelling, often provide sufficient reason, but deductions oblige. Smolin thus presents a general argument for the elimination of ideal elements.

His deduction from the principle of sufficient reason—which he construes as the statement "In a complete theory of the universe, every question of the form

[33] [41], 246.

[34] As Smolin remarks, if the theory "were not complete in this sense, [then] we would not be very interested in its further development" ([41], 246).

[35] Leibniz writes: "Our reasonings are based on *two great principles, that of contradiction* ... And *that of sufficient reason*, by virtue of which we consider that we can find no true or existent fact, no true assertion, without there being a sufficient reason why it is thus and not otherwise, although most of the time these reasons cannot be known to us" ([28], 217).

[36] We might wonder whether or not this argument is tautological; for, Smolin has crafted his definition of ideal elements so that their elimination from physical theory is a necessary condition for quantum cosmology. Since his definition does not make ideal element elimination a sufficient condition as well, Smolin's proposal is nontrivial.

Why is the world this way rather than that way? must have an answer."[37]—proceeds as follows. He proffers two premises.

> *First Premise* There should be no arbitrary choices made in the construction of a complete physical theory.[38]
>
> *Second Premise* Any time such a choice must be made, one is putting in by hand something that one would like explained by a deeper, more fundamental theory.[39]

He draws this conclusion.

> *Conclusion* Thus, the principle of sufficient reason can be taken to mean that, in a complete physical theory, there should be no ideal elements.[40]

The first premise is a rephrasing of Smolin's version of the principle of sufficient reason. The second premise seems a reasonable assessment of an arbitrary factor's introduction into a physical theory.[41] Does the conclusion now follow? Indeed, as Smolin has construed the principle of sufficient reason and defined ideal elements, the former entails the elimination of the latter.

Which component of the argument—the principle of sufficient reason or the definition of ideal element—performs the brunt of the work? The argument appears to thoroughly meld these two components, but to what extent has Smolin engineered the definition of ideal elements to make them susceptible to elimination via the principle of sufficient reason? The notion of an ideal element already stems from Leibnizian considerations, which the principle of sufficient reason, as a central tenet of his philosophy, imbues. I am therefore inclined to identify the principle of sufficient reason as the *primum mobile* of Smolin's argument. Indeed, the principle of sufficient reason can wield considerable deductive power because of its generality of formulation and of application.

Shortly following the above argument, Smolin discusses the principle of sufficient reason's role as a completion criterion for physical theories. He writes

> Any question we may ask in a given theory that fails the test of sufficient reason thus represents an opportunity for a future theory. As long as we do not have this future theory, we must concede that whenever such a question is left open, a theory might arise that resolves this question and yet agrees with the testable parts of our present theory ... as long as the possibility of this happening is open, we cannot claim with confidence that the present theory is complete.[42]

Initially this argument seems plausible, but upon reflection it raises serious philosophical difficulties. First, Smolin's reasoning suggests that there exists a purely theoretical test for a physical theory's applicability to the entire universe: does the theory employ ideal elements? Presumably, Smolin does not envision

[37] [41], 244.
[38] [41], 245.
[39] [41], 245.
[40] [41], 245.
[41] As I discuss shortly, however, this statement is not unproblematic.
[42] [41], 245.

such a test replacing experiment;[43] rather, once we have discarded all of the theories that fail this applicability test, we distinguish empirically between the remaining candidates.

Second, that we can never have confidence in the completeness of a present theory follows as a subsidiary conclusion. When a present theory fails the test of sufficient reason, we can have confidence in its incompleteness. If, however, a present theory satisfies the test of sufficient reason, then how can we have confidence that we have asked of it all of the appropriate questions? This concern may not be an issue in practice: do we not always treat scientific theory as incomplete in this sense? Is not this a hallmark of scientific knowledge? More importantly, though, does this concern pose an obstacle or impediment for Smolin's program based on the elimination of ideal elements? My conclusion suggests that we can never be confident that we have eliminated all of the ideal elements from a theory. Accordingly, that theory could not serve as a quantum cosmology. This consequence seems an insuperable barrier to Smolin's plan, yet again it may not prove a problem in practice. Taking Smolin's advice we might attempt to develop physical theories devoid of ideal elements. This effort might produce highly successful theories even if we do not achieve the goal of complete ideal element elimination. The pertinent question now becomes 'Does the attempt to eliminate ideal elements appear a promising route to theory building?'. I return to this inquiry in §3.2 when I consider Smolin's maximal variety proposal.

These latest concerns raise some broader philosophical issues regarding the elimination of ideal elements. To what extent can human scientists develop physical theories devoid of ideal elements? Do we rely on ideal elements in some ineliminable way in constructing and interpreting physical theories? These two questions are inherently difficult to answer, yet I would like to register several remarks. As Smolin notes, we have never constructed a physical theory completely free of ideal elements. He cites general relativity with cosmological boundary conditions as our best effort; yet, when working with this theory, we often introduce ideal elements—for instance, the aforementioned assumptions of cosmological homogeneity and isotropy—to render the theory more practicable. This difficulty to work with the unadulterated theory tells against our ability to make sense of theories without ideal elements. Of course our difficulties might merely reflect our unfamiliarity with this type of theory: as we develop the skills to cope without ideal elements, this objection would vanish.[44] Though, we might attempt to argue—along the lines of Niels Bohr's philosophy towards quantum theory—that we require the crutch of ideal elements—analogously to the classical side of the Heisenberg cut—to interpret physical theory. Furthermore, will we always be able to replace an ideal element with a dynamical analogue? If this proves the case, then our crutch will always be there to offer support. If the contrary proves true, then we must rely on a novel theoretical insight to save our theory, perhaps akin to the abandonment of the luminiferous

[43] Smolin's other writings—see, for example, chapters thirteen, seventeen, and nineteen of [43]—indicate that he firmly supports the experimental method. There is a sense, nevertheless, in which the principle of sufficient reason, taken to its logical extreme, demands a unique theory of the universe.

[44] Smolin further asserts that we do not understand general relativity with cosmological boundary conditions "very well ... as a dynamical system, in ways which are important for the problem of constructing the quantum theory" ([41], 231-232).

æther.

Smolin recognizes Barbour-Bertotti theory as a simplified case in which the elimination of certain ideal elements is transparently achieved. Our ability to construct this relational reduction of Newtonian mechanics demonstrates that we can at least begin the process of ideal element elimination. Whether or not we can carry the process to its logical conclusion is quite a different question.

I have offered several arguments for and against our ability to create theories without ideal elements. I have one further comment. In a certain regard Smolin attempts to answer the question 'What can we learn of the universe as *de facto* residents?' through his program of ideal element elimination. This inquiry is also difficult to answer, but I suggest that we sidestep it by taking seriously the observation that we necessarily reside within the universe. This fact dictates that our efforts to describe and comprehend the universe necessarily draw only on resources within the universe. Does not this observation thus provide a glimmer of hope for Smolin's project?

3 Directions for Quantum Cosmology

Smolin considers two routes to quantum cosmology. His analysis of ideal elements in quantum mechanics has forced upon him the conclusion that we must modify this theory to make it applicable to the universe as a whole. Both of his proposals accordingly involve a structural modification of standard quantum mechanics, the first moderate, the second drastic. The first seeks a theory of the universe through the canonical quantization approach to quantum gravity.[45] On the basis of his aforementioned analysis, Smolin maintains that there is only one viable route to making canonical quantization succeed, the so-called intrinsic time program.[46] In §3.1 I discuss and critique this route to quantum cosmology. The second seeks a theory of the universe through the development of a completely novel dynamics. Smolin is forced to outline this new theory primarily because of the lack of significant progress on the intrinsic time program. He uses the opportunity to reveal his vision of a truly fundamental theory of the universe. In §3.2 I evaluate his series of ten specific proposals for this theory's form.

3.1 Just Beyond Quantum Theory

Of Smolin's several conclusions concerning ideal elements in quantum mechanics, the most pressing for the development of quantum cosmology is the inner product's reliance on an external time. The inner product forms an integral part of the measurement theory, but an external time is clearly inadmissible. To address this problem Smolin first drafts three criteria that an acceptable measurement theory of quantum cosmology must satisfy.[47] These conditions lead Smolin to consider how the inner product could be constructed intrinsically. In light of the quantum mechanical nature of a dynamical time,[48] Smolin

[45]See [26] for a comprehensive review of the canonical approach.

[46]See [26] for a comprehensive review of the intrinsic time program.

[47]I have elected to skip these specifics because they are not directly relevant to my concerns.

[48]I here refer to the fact that a quantum-mechanical clock necessarily has limited accuracy. For a discussion of these issues, see [31] and [44].

sees only one option: the intrinsic time program.[49]

Besides the dearth of technical progress on the intrinsic time program, there are several arguments against its feasibility in the physics literature.[50] Instead of examining these arguments, I offer a criticism of the intrinsic time proposal inspired by Smolin's own concept of ideal element. The following question captures my concern. Supposing that an intrinsic time variable is identified, to what extent is this variable an ideal element? To judge we must evaluate the intrinsic time variable's status as regards the definition of ideal elements. First of all, an intrinsic time variable does not technically count as an absolute or background structure—this fact constitutes the bulk of Smolin's motivation for maintaining any faith in the program—because it is one of the dynamical variables on the theory's phase space. Nevertheless, an intrinsic time *acts* very much as an absolute or background structure: it performs precisely the same role as does the usual time parameter of standard quantum mechanics, as the formal equivalence of the two defining equations shows. There is thus an explicit sense in which an intrinsic time variable is eligible for comparison to the three criteria of ideal elements. I treat each in turn. First, is an intrinsic time variable contingent? This question's answer depends on the number of variables on the theory's phase space that could function as an intrinsic time. If the variable is unique, then it is certainly not contingent. If we have a choice among two or more candidate variables, then we might deem the intrinsic time contingent. Note, however, that the required form of the constraint equation upon canonical transformation cannot be altered; in this sense there exists little choice in the form of the intrinsic time variable. Second, does an intrinsic time variable play a role in the theory's dynamical equations? The answer is of course a resounding yes; in fact, we have selected the variable for its special dynamical role. Third, is an intrinsic time variable nondynamical? Again, the intrinsic time is, by definition, a dynamical variable. It serves its singular role by remarkable dynamical interaction with the other dynamical variables. This role, however, is so exceptional that the intrinsic time variable appears to be nondynamical in fulfilling it. My analysis suggests that the presence of an intrinsic time would be too good to be true: so faithfully would it mimic its external counterpart that we might well mistake the one for the other.

Before exploring Smolin's second route to quantum cosmology, I would like to touch briefly upon one further issue. In his discussion of the intrinsic time approach to quantum gravity, Smolin assumes that a measurement theory is a necessary supplement to the theory.[51] Of course we intend to perform experiments—we must test our candidate quantum cosmologies—so of course we require a measurement theory. My point, however, concerns the relation of our theory of quantum cosmology to its associated measurement theory. A quantum cosmology is a theory of the universe, and measurements are natural phenomena within the universe; therefore, a theory of quantum cosmology must include its measurement theory, and we possess no reason to differentiate the two. These remarks relate to the concept of Einstein-Feigl completeness, the re-

[49] See the second appendix for a brief discussion of the intrinsic time program.

[50] See [25, 2, 44].

[51] As we shall see in the next subsection, Smolin neglects issues of measurement and interpretation in the presentation of his second proposal. It is unclear if he has disregarded these concerns or if he has registered the force of my ensuing comments.

quirement that a physical theory account for its confirmation basis.[52] I contend that any attempt to create a quantum cosmology must eventually confront this issue. The degree to which a putative quantum cosmology unifies our physical knowledge will determine whether or not Einstein-Feigl completeness is a concern. For instance, the canonical quantization approach to quantum cosmology currently employs too primitive a characterization of matter to make Einstein-Feigl completeness an issue. On the other hand, Smolin's second proposal for quantum cosmology aspires to a level of fundamentality on which Einstein-Feigl completeness must be accomplished.

3.2 Well Beyond Quantum Theory

Given the paucity of results from the intrinsic time program, Smolin considers "how we might invent a new physical theory that could be a quantum theory of the universe as a whole."[53] He decides to set forth a list of ten "new principles and new hypotheses about nature" to guide "the discovery of such a theory."[54] In §3.2.1 I state each of Smolin's proposals, discussing in turn their motivations and merits as fundamental ideas for a theory of the universe based on contemporary physics. When I have finished this analysis, I reflect on the success of his proposals as guides to future physics and of his framework in achieving a physics free from ideal elements in §3.2.2.

3.2.1 The Vision

Smolin clearly intends to frame a fundamental theory of the universe with his ten proposals. We must keep this intention in mind while I present and assess his vision.

First Proposal *The randomness of quantum mechanics is a consequence of its being necessarily a theory of only a small portion of the universe.*[55]

This proposal establishes the sense in which the theory being sketched would constitute a *quantum* cosmology: quantum mechanics emerges from a more universal theory as a description of suitably local physics. Smolin extensively illuminates the manner in which he envisions this emergence proceeding. He begins by asserting that his proposal "is the only possibility ... fully consistent with the principle of sufficient reason."[56] This comment seems to reflect his belief that the probabilistic nature of quantum mechanics is incompatible with the principle of sufficient reason. For, we may always ask the question 'Why did that outcome occur?', but quantum theory can provide no more reason than a probability of occurrence. Supposing that quantum mechanics is susceptible to the test of sufficient reason, we need an explanation for the theory's probabilistic nature.[57] Whether or not Smolin's explanation is the *only* acceptable

[52] See [16, 19], [21], especially pages 58 through 61, and [22], especially pages 38 through 41.
[53] [41], 267.
[54] [41], 267.
[55] [41], 267.
[56] [41], 267.
[57] Alexander Pruss has recently commented on this issue: he attempts to reconcile quantum mechanics with the principle of sufficient reason. See [37], especially pages 160 through 170.

one is a separate matter; I postpone its consideration until I have discussed the remainder of Smolin's commentary.

Smolin envisages a deterministic theory of the universe involving nonlocal interactions. He therefore accommodates both the principle of sufficient reason's demand that measurement outcomes have causes and the experimental disproof of the Bell inequalities'[58] demand that interactions be nonlocal. On this view the entire universe essentially consists of a network of nonlocal interactions. When attempting to construct a theory of local physics, we would have to appropriately average over the nonlocal degrees of freedom. Smolin suggests "that the resulting statistical theory would be quantum mechanics."[59]

Smolin's proposal is eminently plausible. In addition to the motivations that he cites, there is another, perhaps more obvious, reason to claim quantum mechanics as a theory of local physics. Experience, both casual and experimental, indicate that quantum-mechanical phenomena only occur on sufficiently small distance scales. Attempts to observe macroscopic superpositions may challenge our experience in several years, but for now the quantum appears confined to the minute.

As promised, I return to the question of the uniqueness of Smolin's proposal as regards the principle of sufficient reason. I first note that there is in fact a well-developed deterministic and nonlocal theory from which quantum mechanics emerges: the de Brøglie-Bohm pilot wave theory.[60] There are also other approaches—for instance, suitable developments of dynamical collapse models[61]—that have the potential to reduce quantum-mechanical phenomena to a deterministic theory. Smolin thus concludes prematurely that the principle of sufficient reason singles out his proposal.

Second Proposal *There is a deterministic theory that describes the universe as a whole. It is completely relational and nonlocal.*[62]

Smolin expounds.

> [This theory] would be relational because any theory without ideal elements must contain only dynamical variables that involve relational quantities.[63]

As I have explained, Smolin's proposal based on ideal elements is closely related, if not identical, to the relationalist program. Smolin explicitly states that any dynamical analogue for an ideal element is necessarily relational. Thus, a theory devoid of ideal elements is relational: all of its non-ideal elements are relational, and all of its ideal elements have been replaced by relational constructs.

Smolin again invokes Bell's theorem as a motivation for nonlocality; he also states that "nonlocal interactions are essential for the process of replacing universal ideal elements," citing as evidence the situation in the classical Barbour-Bertotti models.[64] Although nonlocality may well prove indispensable for this

[58] See pages 14 through 21 of [11].

[59] [41], 268. Smolin has developed these ideas for the origin of quantum mechanics in [39] and [40].

[60] See [12, 13] for the original proposal. See [45] for a comprehensive account.

[61] See, for example, [35] or [23].

[62] [41], 268.

[63] [41], 268.

[64] [41], 268.

replacement process, classical Barbour-Bertotti theory does not serve as a good indicator. Barbour-Bertotti theory is an instantaneous action-at-a-distance theory, possessing an absolute concept of simultaneity; consequently, it has little to say on the topic of locality. While not of serious import for Smolin's invocation of nonlocality—Bell's theorem is much more significant—this consideration raises a pertinent issue. Smolin makes nonlocality a basic property of his fundamental theory. The concepts of locality and of nonlocality employ notions of spacetime structure in their definitions. As we shall see shortly, however, Smolin makes space and its structure an emergent property of the universe. To invoke nonlocality at a fundamental level, therefore, threatens a logical contradiction.

Third Proposal *The causal topology of this fundamental theory reflects the history of interactions among particles in the universe rather than the present spatial relations.*[65]

This proposal's message is intuitive and appealing: in specifying the universe's state we must take a completely holistic view. It also resonates with Leibniz's conception of the complete interconnection of things.[66] Again, we must, however, ask if Smolin has attempted proverbially to run before he can walk. Three of the concepts he here employs—causality, history, and spatial relations—do not enter his theory at a fundamental level.[67] Like locality, causality involves a notion of spacetime structure; history invokes a notion of time evolution; and spatial relations involve a notion of distance. If we grant Smolin the benefit of the doubt—assume that by 'causal' he refers to the more general notion of causation, not the specific notion of causality—then this usage no longer presents a contradiction.[68] Furthermore, as we shall see in the next three proposals, Smolin sketches the emergence of spatial relations and relative distance and elevates time to a basic notion, thereby licensing to a certain extent his usage of spatial relations and history.

Fourth Proposal *The dynamics of the fundamental theory are such that in the thermodynamic limit in which the number of fundamental particles goes to infinity, spatial relations emerge as a good approximate description of the causal relations among particles in the system.*[69]

Smolin thus concludes that space is a completely emergent phenomenon; moreover, since the underlying theory is relational, space necessarily inherits this property. Smolin foresees that in this same limit classical physics—presumably general relativity—emerges as the universal theory's dynamics. He gives little indication of why classical physics should become an appropriate description in this thermodynamic limit. I surmise that he banks on the Machian idea that the sheer multitude of particles will provide a system of reference points mimicking spatial relations.[70]

[65] [41], 268.

[66] See pages 152 through 153 of [27] and §§56-62 on pages 220 through 221 of [28].

[67] Causation, meaning "the production of an effect," is more general than causality, which refers to the deterministic structuring property of spacetime ([17]).

[68] I must admit, however, that I interpret his usage of causal to connote the latter meaning.

[69] [41], 269.

[70] See, for instance, pages 262 through 265 of [1].

Smolin has now elucidated how both pillars of contemporary physics—general relativity and quantum mechanics—emerge from his hypothetical fundamental theory. Given his explanations of their emergence, how should we place the fundamental theory on the classical-quantum spectrum? Or is this spectrum unsuited to Smolin's vision?

The theory's key attributes include determinism, relationalism, nonlocality, holism, and, as he shall propose shortly, finitude. Neither general relativity nor quantum mechanics incorporates all of these characteristics. Both accommodate determinism, holism, and finitude in certain respects; while general relativity leans more towards relationalism, quantum mechanics is manifestly nonlocal. Smolin himself believes that "general relativity is ... a great deal closer to the kind of theory [that] we need in order to do cosmology."[71] As he admits, though, "not all of the obstacles come from the quantum-mechanical side."[72] Perhaps we must concede that consideration of this spectrum is uninformative.

Fifth Proposal *The relative distance between two particles is a measure of their closeness in terms of the topology of the network of relations of the fundamental theory.*[73]

This proposal draws insightfully on Leibniz's principle of the complete notion of a contingent thing. By defining distance through the differences, or, equivalently, the similarities, in relations among fundamental particles—with near particles possessing similar views and far particles possessing dissimilar views of the network of relations—Smolin achieves an elegant, relational, and emergent notion of distance. As he subsequently demonstrates, this conception of distance is readily implemented in his graph-theoretic models.

Sixth Proposal *The fundamental nonlocal dynamical theory has a description in terms of an evolution of its state in a relational time.*[74]

Smolin gives three reasons for "choosing to keep time as a fundamental concept."[75] The first two reasons, by way of physical motivation, are intimately connected. Smolin believes that, in retaining a notion of time, he will more easily recover familiar physics and more clearly understand this recovery. (Of course he sidesteps having to recover time from his fundamental theory.) Smolin also believes that, in retaining a notion of time, he will keep a concept of which our current physical theories provide a firm grasp. Smolin's last reason is of a subjective character: he holds "that the most fundamental observation we make about the world is that events are structured in terms of a flow of time."[76] Smolin is welcome to maintain these beliefs, but we should examine how well they hold up to scrutiny.

First I must elucidate what Smolin means by 'relational time.' Although he makes no other reference to this concept in the paper, the term is defined

[71] [41], 231.
[72] [41], 231.
[73] [41], 269.
[74] [41], 270.
[75] [41], 270.
[76] [41], 270.

elsewhere.[77] There Barbour and Smolin employ ‘relational time’ to designate the notion of time that arises in classical Barbour-Bertotti theory.[78] I discuss this concept in the first appendix.

I now begin my assessment of Smolin’s three reasons for retaining time. His first motivation—that a notion of time will ease the recovery of familiar physics—is speculative: he may or may not be correct, but only time will tell. His second motivation—that a notion of time represents a well-understood aspect of familiar physics—is controversial. We certainly possess an intuitive understanding of time, which we bring not only to the development of physical theory, but also to the employment of physical clocks. In Newtonian mechanics, quantum theory, and perhaps even general relativity, however, we do not understand the time parameter or label in any emergent or reductive sense. What is the status of our understanding of relational time in Barbour-Bertotti theory? In certain respects we understand this time in the aforementioned sense: the time metric is determined by the best matching procedure,[79] which only involves relational spatial data. In other respects we do not understand the relational time. First of all, we introduce an arbitrary time label into the theory to parametrize paths in the relative configuration space. This introduction is clearly necessary and warranted; however, this introduction dictates that the theory include a fundamental variable possessing a time-like[80] topology. Furthermore, since the time metric derives from spatial relations, we need a proper understanding of spatial relations to truly comprehend the emergent relational time. In classical Barbour-Bertotti theory these spatial relations are justifiably assumed to be Euclidean; thus, we do not grasp them in any emergent or reductive sense. Given these last two points, I maintain that we must disagree with Smolin’s second claim and that we must achieve an understanding of space prior to developing an understanding of time.

I would like to rebut Smolin’s third motivation for retaining a fundamental notion of time with two lessons: the first from operational considerations, the second from modern physics. As I stated above, Smolin believes that our observations of the flow of time stand as our most basic worldly experience. This contention is of course debatable. For instance, Barbour maintains that instantaneous configurations represent our most basic worldly experience, and he capitalizes on this viewpoint to develop a novel interpretation for quantum gravity.[81] These beliefs aside, should not Smolin as a physicist consider how time is measured in practice? As many authors before me have noted,[82] whenever we measure time, we actually observe the relative change of two systems: a standard phenomenon (‘clock’) and an interesting phenomenon (‘process’). An abstract time enters nowhere except in the theory that we might employ to describe the clock and the process. Should not Smolin as a physicist also consider the reflection of human experience in contemporary physics? How far is the special relativistic notion of time from that of human experience? The general relativistic notion is surely even more incongruent, yet it underlies our

[77] See page 7 of [9].

[78] Barbour previously referred to this concept as Leibnizian time in [2].

[79] See the first appendix for an explanation.

[80] I do not use ‘time-like’ in its relativistic sense; rather, the adjective ‘time-like’ refers to the continuity and monotonicity of the time label.

[81] See [5], especially pages 2884 through 2885, and [6], especially pages 264 through 267.

[82] For a striking exposition see part 2 of the second chapter’s §VI in [33], especially pages 272 through 273.

most celebrated physical theory of space and time. Smolin aspires to develop an even more fundamental theory applying to regimes far removed from that of the humble environment in which the human race evolved its perception of time. Can he really expect typical human experience to guide the way?

Seventh Proposal *The universe consists of a finite number of particles or fundamental entities.*[83]

This proposal is at once the clearest and the vaguest: the distinction between finite and infinite is perfectly transparent, but what constitute Smolin's "particles or fundamental entities"? The obvious initial response is the particle content of the standard model or an appropriate generalization of it. This reply, however, is poorly substantiated. I would expect Smolin to indicate this reply if he intended it. He clearly does not, however, since he does not even commit to the existence of particles.

What then do we take as the theory's fundamental entities? Smolin recognizes (in an endnote) the necessity of a response but offers none.[84] Evidently, Smolin thinks that this concern is not sufficiently pressing. I maintain that he is terribly mistaken. First of all, recall the motivation for retaining aspects of both general relativity and quantum mechanics in a quantum theory of gravity that I briefly discussed in §1.2. The first theory excels in its description of space and time while the second theory excels in its description of matter and energy. Since Smolin seeks a unification of these two theories—moreover, a unification in which space emerges from the interactions the universe's constituents—he cannot avoid the question at this paragraph's start.

Smolin is also concerned with the origin of gravitation.[85] General relativity teaches us that gravitation is intimately intertwined with space, time, and matter; specifically, general relativity has us conceive of gravitation as arising from the geometry of spacetime induced by the presence of matter. Now, in Smolin's universal theory, space emerges from the relations of interacting fundamental entities. If gravitation is written into emergent space as general relativity would dictate, then we must understand the nature of his theory's fundamental entities. How else can we elucidate gravity's origin? In my overall appraisal of Smolin's vision, I return to this issue in light of the conjectured theory's fundamental nature.

Eighth Proposal *Quantum physics emerges as a description of the fluctuations around the thermodynamic limit in which classical mechanics on a spatial background emerges from the fundamental theory.*[86]

This is Smolin's second comment on how quantum mechanics fits into his scheme. At first glance this eighth proposal differs markedly from the first: the first makes explicit reference to the role of relative scale in the emergence of quantum mechanics while the eighth explains the manner in which this emer-

[83] [41], 270.

[84] "Many people, from Einstein to present-day advocates of string theory, have felt that this was not sufficient; a theory that purports to be a theory of the whole universe, they argue, should also have something to say about what is in that universe" ([41], 281).

[85] As we shall see, before presenting his final two proposals, he raises this question.

[86] [41], 271.

gence proceeds. Are the two proposals in fact compatible? We should first understand precisely what Smolin now proposes.

As he previously suggests, in the thermodynamic limit classical spatial relations emerge as an accurate description of the theory's dynamics. By classical we took him to mean general relativistic. Now, in certain regimes and on sufficiently small length scales, a general relativistic spacetime is well approximated by a special relativistic spacetime, which in turn is well approximated by Newtonian absolute space and time provided that relative velocities remain significantly below the speed of light. We thus grasp how classical mechanics emerges in the thermodynamic limit of Smolin's speculative theory. Smolin also proposes that the thermodynamic limit is approximate because the universe consists of a finite number of fundamental entities. His eighth proposal is now more comprehensible: quantum mechanics describes the fluctuations about the thermodynamic limit in regions of sufficiently small scale to be described by classical mechanics in an exact thermodynamic limit. Standard quantum mechanics employs a Newtonian spacetime background. Accordingly, for the theory to be applicable, approximately or exactly, the actual spatial background, emergent or absolute, must be Newtonian spacetime. Since Minkowski spacetime provides a more accurate description, relativistic quantum field theory emerges as a better characterization of these fluctuations. Thus, we do require the thermodynamic limit for quantum mechanics to be a good description.

Is this proposal equivalent to the first? Recall that the first proposal attributed quantum-mechanical phenomena to the statistical averaging over nonlocal degrees of freedom to obtain a local physics. In principle this procedure has no need for a thermodynamic limit, approximate or exact, but I have shown how an approximately Newtonian background, necessary for the applicability of quantum mechanics, requires a thermodynamic limit on Smolin's scheme. Furthermore, the first proposal's process of statistical averaging invokes no preexisting fluctuations; it creates fluctuations by ignoring information in nonlocal degrees of freedom. We have thus uncovered a serious tension between Smolin's two explanations of the emergence of quantum-mechanical phenomena.

In which proposal should we lay more stock? I contend that the first proposal is better motivated. As I previously discussed, it provides a compelling explanation for why quantum mechanics applies so strikingly to microscopic scales. Alone the first principle cannot explain the emergence of Newtonian spacetime that quantum mechanics requires, but, augmented with the fourth proposal, we can account for this circumstance. In conjunction with the seventh proposal, the fourth proposal must not, however, entail the eighth proposal. The fluctuations to which Smolin alludes in this latter proposal are fluctuations of the emergent spacetime relations around Newtonian spacetime relations. Such fluctuations do not give rise to quantum-mechanical behavior; though, they do affect the applicability of that theory. I therefore submit that we ignore Smolin's eighth proposal.

Smolin interrupts his presentation to identify three "glaring problems" left unsolved by his proposals thus far.[87]

> *First Problem* How can the dynamics of the fundamental relational theory be chosen so that a low-dimensional space emerges as an

[87] [41], 271.

> appropriate description of the network of relations in the thermodynamic limit?[88]
>
> *Second Problem* We must explain how the principle of inertia and the relativity of inertial frames emerges from a theory in which all distances to begin with are both relational and absolute.[89]
>
> *Third Problem* We would like to know where in this scheme gravity comes from, and why it is weaker by many orders of magnitude than the other forces.[90]

Smolin comments briefly on these issues. Starting with the second, he notes that we have a clear indication for how to solve this problem because Barbour-Bertotti theory accomplishes this aim for classical mechanics.[91] On the other hand, he claims that the first problem will prove most difficult. Indeed, Smolin maintains that the recovery of 3-dimensional space is the key to unlocking his proposed theory's development. With his graph-theoretic models he makes a preliminary attempt to address the emergence of low-dimensional space. Although I do not discuss this part of his article, I note that his attempt is intriguing and promising. Finally, Smolin admits that he currently has "no good answer" to his third problem.[92] Considering my criticism of his seventh proposal, this admission comes as no surprise.

Smolin now moves on to the presentation of his graph-theoretic models, in the midst of which he states the last two proposals.

Ninth Proposal *In a discrete theory of relations, the variety is the fundamental dynamical quantity. The fundamental dynamical principle is that the universe evolves in such a way as to maximize its variety.*[93]

Smolin's ninth proposal deserves special attention for two reasons: first, it invokes the Leibnizian emphasis on variety as a salient feature of the natural world, and, second, it presents the guiding dynamical principle of this conjectured universal theory. After discussing the intended notion of variety, its motivations, and its place within Leibniz's philosophy, I critique Smolin's principle of maximal variety both as a suggestion for the creation of structure and in relation to the arrow of time.

Smolin uses variety in its colloquial sense: the quality of being diverse, the absence of uniformity.[94] Why does he elevate so ordinary a concept to the status of fundamental dynamical quantity? Barbour compellingly makes the case for variety.

> Science in general and dynamics in particular is only made possible by the fact that we perceive variety. This perceived variety is

[88] [41], 271.
[89] [41], 271.
[90] [41], 271.
[91] Beware of Smolin's perplexing juxtaposition "relational and absolute". I take 'relational' to indicate that the theory involves only relational notions of distance; I take 'absolute' to indicate that at the fundamental level the theory does not involve the notion of relative, or perspectival, frames of reference.
[92] [41], 271.
[93] [41], 277.
[94] [46]

> the starting point of all science. There is however a pronounced tendency in science to degrade variety and operate as far as possible in terms of homogeneous and uniform substances ... A key task in science is therefore to identify and quantify the *salient* variety in the phenomena under investigation ... the aim of dynamics is, at its most general, to characterize change of variety quantitatively ... Ultimately, the reason why perfect uniformity cannot serve as the *practical* basis of a quantitative science is that perfect uniformity is nothing ... variety must provide its own terms of reference for describing the way in which it is changing.[95]

Barbour also illuminates how variety forms an integral component of Leibniz's philosophy. He remarks first that "variety is the starting point of Leibniz's ontology,"[96] expounding

> that the whole tendency of Leibniz's philosophy is to present science, not as the explanation of perceived variety in terms of something which is as uniform as possible, but rather as the recognition of order and unity within diversity.[97]

Furthermore, "following Leibniz's epistemology, existence is identified as the possession of attributes that distinguish—the possession of positive variety."[98] The "interconnection of accommodation of all created things to each other, and each to all others, ... is the way of obtaining as much variety as possible, but with the greatest order possible."[99]

This emphasis of Leibniz's philosophy underlies the relationalist program.

> All these different [forms of dynamics hitherto developed] are based essentially on the idea that the change of variety is to be expressed by means of certain uniform standards ... the question at the heart of the criticism of Newtonian dynamics by Leibniz, Berkeley, and Mach concerns precisely the use of *any* uniform standard in dynamical theory ... [the epistemological criticism of Newtonian dynamics] centres on the discrepancy between theory, in which change of variety is referred to a uniform standard, and actual practice, in which change and variety are in fact referred, not to space and time, which remain invisible, but to *other variety* ... We have thus the minimal ontological principles of the relation[al]ist standpoint: the existence of things is established through perceived variety and abstract uniformity is nothing.[100]

We have grasped how variety could plausibly form the basis for a reconception of physics and how Leibniz envisioned its maximization accounting for the universe's structure. I must now ask an all-important question. Does Smolin's dynamical principle dictating variety maximization possess the organizing power to generate the structure that we observe in the universe? We cannot expect

[95] [1], 251-253.
[96] [1], 251.
[97] [1], 251-252.
[98] [4], 125.
[99] [28], 220.
[100] [1], 252-254.

a detailed answer to this broad inquiry primarily because investigations into Smolin's proposal are still far too limited. Despite the limited development, however, I believe that the few attempts to build interesting structure from the principle of maximal variety show promise and potential. Smolin already takes the first steps towards solving his first glaring problem. Barbour begins to develop further Smolin's ideas, preliminarily sketching how quantum-mechanical phenomena could arise.[101] Barbour and Smolin construct model systems in which three interesting forms of structure derive from the extremization of variety: "the dynamics is deterministic globally, but stochastic on the smallest scales"; "[a]t an intermediate scale structures emerge which are stable under stochastic perturbations of smaller scales"; and "in the near to extremal configurations . . . both short ranged repulsive forces and long ranged attractive forces" emerge.[102] All three of these instances of structure building from maximal variety do not in fact employ the specific form of Smolin's proposed dynamical principle: they do not work on the evolution towards maximization of variety. This fact does not degrade the significance of variety and its extremization as a guiding idea; it merely suggests that the specific form of Smolin's initial proposal might not prove the best instantiation of the maximal variety doctrine.

To further this last thought, I consider the relation of Smolin's specific proposal to the third most popular physics problem for philosophers: the arrow of time. Smolin proposes that the universe evolves towards states of increasing variety. This conception is strikingly reminiscent of our current scientific belief in the universe's evolution towards states of increasing entropy. How might variety and entropy be related? With only an intuitive sense for the quantification of variety, we might have difficulty connecting it to (one of) the specific definitions of entropy, but perhaps our intuition will prove sufficient for now. Variety is nearly synonymous with diversity. Although entropy is often associated or equated with disorder—or, more accurately, identified as a measure of disorder—I suggest that the statistical definition of entropy will prove more useful. In this sense entropy is effectively a measure of the probability of a given state within an ensemble of states. The universe's evolution towards states of greater entropy thus becomes evolution towards more probable states. This interpretation has the important consequence that the universe originated in a highly improbable state. For variety to relate to entropy, states of greater variety must be more probable. *A priori* I see no reason why this must hold true. When we look to our physical knowledge of the universe's evolution, what light do we shed on this possibility? Current cosmological theory predicts that the universe will continue to expand forever, its mutual gravitational attraction insufficient to balance or overcome its outward acceleration. The universe will thus become increasingly dilute, and its myriad clusters of matter will become increasingly concentrated.[103] If vast expanses of virtually empty space punctuated by isolated concentrations of matter correspond to high variety, then perhaps the connection between entropy and variety is strong. This fact would have three remarkable consequences: first, Smolin's proposal would solve the problem of the arrow of time;[104] second, it would indicate an intimate connec-

[101] See [3], especially pages 1067 through 1072.

[102] [10], 1.

[103] The statistical mechanics of self-gravitating systems is counterintuitive: clumpiness as opposed to uniformity is the mark of high entropy. See [24] for a discussion of these predictions.

[104] Barbour has a similar proposal for the arrow of time's origin. See chapter twenty-two of

tion between variety and gravitation; and, third, variety and its maximization would find a link to a well-developed branch of physical theory—statistical mechanics. Of course this is probably too much to hope for, but only specific implementations of Smolin's dynamical principle will tell.

Tenth Proposal *The principle of maximal variety drives the tuning of the physical constants so that systems of arbitrary complexity can evolve and maintain themselves in the universe. In some future physics it will account for both the existence of gravitation and the existence of life.*[105]

Smolin's last proposal is a mixture of bold, creative ideas and poor, misplaced ideas. The former come in the first clause as an inventive explanation for the physical constants' values; the latter fill the proposal's remainder. As I mentioned in §1.2, physicists currently view as pressing the problem of the determination of the values of our universe's physical constants. In particular, a widespread sentiment maintains that these values are statistically improbable or, in physics jargon, fine-tuned. Although Smolin does not detail its functioning, he suggests a robust mechanism for the dynamical determination of these values.[106] The proposal's second clause—"so that systems of arbitrary complexity can evolve and maintain themselves in the universe"—completely lacks import: complex systems *have* developed and endured, so the dynamical principle of a theory describing our universe *must* account for such phenomena. The last sentence is equally unenlightening in its second prediction as life certainly falls into the category of evolved and maintained systems of remarkable complexity.

In light of previous discussion, the last sentence's first prediction deserves our attention. Again, any candidate fundamental theory must explain the phenomenon that we call gravitation. As we currently understand this phenomenon, gravitation is a manifestation of the form of spacetime arising from the distribution of matter and energy. Since the notions of space, time, matter, and energy are conflated with the notion of gravitation, we appear to require an understanding of the former four for an understanding of the latter one. As my analysis of the previous nine proposals has shown, Smolin only provides a reasonable approach to the first of these four concepts. In particular, without a description of the objects—fundamental particles, entities, events, or what have you—on which our measure of variety is based, the principle of maximal variety cannot act. Smolin still seems very far from solving his third glaring problem.

3.2.2 The Appraisal

Now that we have examined the entirety of Smolin's second approach to quantum cosmology, I would like to comment on the program as a whole. Recall that before stating his first hypothesis, Smolin warned us of the speculative and schematic nature of what followed. I must agree with this assessment: Smolin sketches several compelling conjectures that deserve further attention and investigation, but his warning does not serve to excuse those speculations that

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[6].

[105] [41], 279.

[106] In [42] Smolin develops an alternative mechanism for the tuning of physical constants that applies natural selection to the cosmos.

fail to hold up to scrutiny. I first identify his proposal's three aspects that strike me as most significant and insightful. I then identify the two aspects that strike me as most requiring rethinking and improvement. To this end I suggest how each of the latter two aspects might find resolution in Smolin's program.

His conjectured theory has three principal highlights: the hypotheses that quantum mechanics arises as a statistical theory of local physics, that causal topology and relative distance emerge from the complete interconnection of the universe, and that the maximization of variety performs a fundamental dynamical role in structuring the cosmos. Interestingly, all three of these ideas derive from Leibnizian philosophy. As Smolin himself informs us, the first hypothesis is the only explanation of quantum-mechanical phenomena compatible with the principle of sufficient reason. The second hypothesis draws heavily on the *Monadology*'s vision of the universe's organization. Though in a modern guise, the third hypothesis realizes Leibniz's idea that the world contains "as much variety as possible, but with the greatest order possible."[107]

His conjectured theory also has two principal pitfalls: it lacks any indication of what constitute the universe's fundamental entities, and the retention of time as a basic notion seems unjustified. Excepting these two pitfalls, Smolin's theory appears a promising attempt to push forward our understanding of the universe. To prevent these two obstacles from impinging upon further development, can we readily resolve or dissolve them? In the case of the second fault, a solution suggests itself: simply deny time a fundamental status. This suggestion may not seem like much of a solution since now we must additionally recover time from a more basic description. As I have indicated, though, we appear to require a thorough understanding of space prior to establishing a proper understanding of time. Since Smolin already calls for the emergence of space, perhaps an emergent time will come along for the ride. Granted, the recovery of time might not prove a cakewalk, but, as Smolin contends, the derivation of space will be much more difficult. The denial of time also leads to the elimination of the last apparent ideal element in Smolin's theory, namely, time itself.

His theory's second fault seems like an entirely different predicament. As I indicated in my criticism of Smolin's seventh proposal, the nature of the universe's fundamental entities is essentially tied to the foundations of everything. There might, however, be one Leibnizian loophole—a wholly monadic approach. This is perhaps the position at which Smolin hinted, but he does not come close to explicitly endorsing it. According to the *Monadology*, the world consists entirely of monads, fundamental entities *par excellence*—"true atoms of nature"—which possess the capacity to bear certain attributes.[108] These attributes are mirrored in the universe by the network of relations between the monads in such a way that each "monad is, in fact, simply *the world as seen from its particular point of view*."[109] This idea resolves an apparent tension in Leibniz's philosophy. Monads are at first glance absolute and independent. If we take relationalism to its logical conclusion, however, then the existence of such entities seems a contradiction. Conceiving of monads as consisting essentially of their relations

[107] [28], 220.
[108] [28], 213-214.
[109] [4], 130. Leibniz writes: "This interconnection or accommodation of all created things to each other, and each to all the others, brings it about that each simple substance has relations that express all the others, and consequently, that each simple substance is a perpetual, living mirror of the universe" ([28], 220).

to one another relieves the tension.

This line of thought inspires my solution to Smolin's problem of fundamental entities. I suggest that we do not hypothesize any attributes, excepting existence, for our fundamental constituents; rather, we only consider possible relations between them. Here the example of a mathematical graph is apposite: its vertices do not have any basic characteristics; they merely have relations to other vertices as expressed by their connectivity. We must of course still determine what relations to allow amongst the fundamental entities. Smolin and Barbour have begun from the first natural relation: connected or not connected. Whether or not this elementary relation will suffice remains to be determined, but, perhaps, on this view the most important question will become what relation works.

4 A Lot of Leibniz, A Bit of Barbour

I have now inspected the totality of Smolin's quest for quantum cosmology from the elimination of ideal elements. To conclude I analyze the extent to which Smolin draws on Leibniz's and Barbour's thought in developing and implementing his proposal. I hope to touch upon the following questions. To what extent has Smolin just rebranded Leibniz's philosophy in a modern guise? How indebted to Barbour's interpretation of Leibniz's philosophy is Smolin? Where is Barbour's work on relationalism most evident? What aspects represent novel Smolin?

Smolin open his article with an extensive epigram: a series of five quotations filling nearly two pages. The first two excerpts come from Leibniz's *On the Principle of Indiscernibles* and *Monadology*. They reference the principle of sufficient reason ("...this important principle, that nothing happens without sufficient reason ..."), the relational nature of space and time ("...space to be something purely relative, like time ..."), and the complete interconnection of existence ("...there are no purely extrinsic denominations because of the interconnection of things ...").[110] Smolin's links to Leibniz are explicit from the outset.

Smolin opens his acknowledgments with a profuse thanks: a note to Barbour's impact on his viewpoint. He credits Barbour with "awakening [his] Leibnizian tendencies" and cites "the extent to which [Barbour's] views have influenced those expressed" in this paper.[111] Smolin's debts to Barbour are explicit by the end.

Of course we all attribute aspects of our outlooks and opinions to the influences of specific people who have notably affected our thinking. I certainly do not intend to write off Smolin's work as purely derivative; quite the contrary, I myself find many of his ideas equally as compelling as he finds those of Leibniz and Barbour. (Unsurprisingly, I too am attracted to Leibnizian and Barbourian thought.) Nevertheless, I believe that we will further our analysis and understanding of Smolin's program through close examination of his bonds to Leibniz and Barbour.

[110] [41], 228.
[111] [41], 280.

4.1 Deploying the Principle of Sufficient Reason

Smolin prefaces his two arguments from the principle of sufficient reason with the following proviso.

> While I do not expect to convince an audience of physicists with *a priori* arguments, let me not leave this topic without indicating what sort of arguments I have in mind.[112]

He then deploys the principle of sufficient reason in its full glory. As I have demonstrated, the arguments for externality and for elimination rely heavily on Leibniz's principle for their deductive success. I have difficulty envisaging the arguments proceeding by different routes—especially routes acceptable to a physicist—and this very observation is surely the motivation for his above proviso. We might wonder why he bothers with the arguments at all given his audience; I suspect that, even if the arguments are judged indecisive by his audience, they still play a motivating role.

I would instead like to ponder the following question. Why does Smolin invoke only the principle of sufficient reason? True, this principle is the second of Leibniz's central tenets from which his entire philosophy follows. Yes, Smolin takes Leibniz's argument against absolute space and time based on the principle of sufficient reason as the "prototype" for his argument for ideal element elimination.[113] But, the principles of contradiction and of sufficient reason are not Leibniz's only well-known tenets. Leibniz also defended the principles of the identity of indiscernibles and of the complete notion of a contingent thing.[114] Given his audience of physicists, why does Smolin not appeal to either of these principles? Both the identity of indiscernibles and the complete notion of a contingent thing are quasi-logical statements; they are also grounded in observation and experience to a certain extent. Accordingly, a physicist would find them eminently more appealing and convincing principles than that of sufficient reason with its theological overtones. Moreover, in physics we are concerned with explanations, not with reasons.

Barbour cites the identity of indiscernibles and the complete notion of a contingent thing as relationalism's two primary epistemological principles, extensively demonstrating how they inform and clarify the Leibnizian position. Given his relational leanings, why does Smolin not incline to these two principles? They could help to motivate not only the elimination of certain ideal elements, but also several of the ideas that Smolin presents in his conjectured fundamental theory. Would not framing these aspects of his program with the identity of indiscernibles and the complete notion of a contingent thing illuminate two further overarching Leibnizian structures?

Of course there is an economy in drawing on just one principle, but not if that principle carries excessive metaphysical baggage. Now, the identity of indiscernibles and the complete notion of a contingent thing do not push through Smolin's two key arguments, but they could assist in the presentation and comprehension of his approach to quantum cosmology. Since Smolin evidently ex-

[112] [41], 244.

[113] [41], 244. See page 325 of [29] for Leibniz's argument.

[114] The former states that any two objects possessing exactly equivalent properties are in fact the same object; the latter states that, in order to identify completely a single object, we must specify that object's every attribute to such an extent that we can then deduce everything that could logically follow about that object.

pects *a priori* reasoning to provide only motivation, I do not understand why he neglects these two Leibnizian tenets.

4.2 Maximizing Variety

The very notion of variety is intimately connected with the identity of indiscernibles and the complete notion of a contingent thing. The former principle serves as a detector of uniformity, an enforcer of variety. The latter principle serves as a means to characterize and relate variety. Despite Smolin's neglect of these connections, he makes great strides with the concept of variety.

Leibniz hatched the conception of a maximally varied universe exhibiting remarkable order nonetheless. On his picture, ignoring for the moment the extramundane, variety brings the world into existence: all monads—"the elements of things"—are "different from each other."[115] Barbour persuasively argued for grounding physics in variety. With Bertotti he demonstrated the power of this idea by exposing its structuring role in classical dynamics. Although Barbour pointed to the quantification of variety as "a key task of science," Smolin made the great leap forward.[116] In deploying the maximization of variety as a mathematical principle for guiding the universe's dynamics and creating the universe's structure, Smolin gives Leibniz's vague scheme a precise formulation, turning Barbour's suggestion on its head by making salient not just the quantification of variety, but the very quantity of variety.

4.3 Relation to Relationalism

Throughout my essay I have considered the relationship between Smolin's program based on ideal elements and the relationalist program inspired by Leibniz. I would now like to draw a final conclusion regarding the nature of this relationship. Effectively, this consideration boils down to the questions of how much Smolin has extracted from Leibniz and Barbour and how much Smolin has created for himself. Allow me first to briefly review the status of this relationship as elucidated so far.

In §2.1 I compared Smolin's ideal elements to two related concepts: Leibnizian relational quantities and uniform background structures. I found that Leibnizian relational quantities are essentially the opposites of ideal elements, except that they incorporate a notion of contextuality. I also found that uniform background structures only diverge from ideal elements in possessing a slightly diminished scope. In §2.2 I compared Smolin's conception to Barbour's conception of the absolute–relative debate's roots. Although their respective emphases differ, I showed how they nevertheless share the same concerns. Thus, it seems that Smolin's ideal elements represent a broader class of constructs than the relationalist would typically deem substantival. What if we take the relationalist position to its logical extreme, abandoning any limit of contextuality? Still, Smolin's concept seems the more encompassing. Recall the previous example of the correspondence between quantum-mechanical operators and classical observables. Smolin identified the correspondence itself as an ideal element. Relationalism seems ill-equipped to brand such constructs substantival even if there are substantival structures lurking in the background. Of course with this

[115][28], 213-214.
[116][1], 252.

augmented generality comes imprecision. As with my several objections to the feasibility of Smolin's program, only the results of theory building will measure the degree to which this imprecision matters.

Smolin's true insight is thus revealed in the generality of his ideal elements over and above the relationalist position. This generality allows him to link the absolute–relative debate and the measurement problem through quantum cosmology. This generality allows him to build a promising program for the development of quantum cosmology. In a definite respect Smolin's insight of generalization consists in the updating of Leibniz's ideas to a world that has witnessed the quantum. We must not let this insight blind us to his debts to Leibniz's thought. First of all, the definition of ideal elements borrows substantially from Leibniz's critique of Newtonian absolute space and time, and in many instances the critique from ideal elements coincides with that from relational quantities. The definition of ideal elements also banks heavily on Leibniz's principle of sufficient reason not only in its crafting, but also in its application. What are we ultimately to conclude of Smolin's program? We have observed Leibniz's influence in many aspects of Smolin's paper. I believe that Smolin is largely indebted to Leibniz for his motivations and his vision and that, although Smolin's work in modernizing Leibnizian thought is significant, part of the credit is due to Barbour.

A Barbour-Bertotti in Brief

Classical Barbour-Bertotti theory provides a relational reduction of Newtonian mechanics: it derives the latter theory from mathematical principles involving only the relative distances between pairs of particles in static configurations. The theory begins from the relative configuration space, the abstract mathematical space of all possible relative configurations of N point particles in 3-dimensional Euclidean space. (We employ the adjective 'relative' to indicate that the set of all possible configurations has been quotiented by the group of translations and rotations of Euclidean space. In other words, the only data required to parametrize a given relative configuration are the $\frac{N(N-1)}{2}$ relative distances between all pairs of particles.) To any two relative configurations we can assign a numerical value that measures the intrinsic difference between these two configurations. This value takes as input only the relative distances between pairs of particles in each configuration; it also depends on how we have envisioned one configuration aligning with the other configuration.[117] Now, via a mathematical extremization procedure called best matching, we can minimize the intrinsic difference by varying over all possible such alignments. Once we have calculated the minimal intrinsic differences between all pairs of configurations, we can create sequences of configurations from any subset of the configuration space. We simply order the subset of configurations such that neighboring configurations have the minimum intrinsic difference between them. We can also parametrize any sequence of configurations in the relative configuration space by a continuous, monotonically-increasing parameter.

With this procedure in place, Barbour-Bertotti theory is ready to work its

[117] To visualize this dependence, consider overlaying the first configuration on the second configuration. I recommend thinking about 1-dimensional configurations for ease of visualization. Clearly, there are an infinite number of ways to realize this overlaying.

magic. The final ingredient is Jacobi's principle: a mathematical procedure for selecting orbits—sequences of configurations—in the relative configuration space. Jacobi's principle was first developed to solve for orbits in Newtonian mechanics. In this setting the procedure requires as input expressions for the potential and kinetic energies of the N particles. To import Jacobi's principle into the setting of Barbour-Bertotti theory, we must replace these Newtonian expressions with their appropriate counterparts. The potential energy poses no problem since it is a function of only the relative distances between pairs of particles. The kinetic energy, however, typically invokes a notion of time evolution. Since time does not enter as a fundamental notion in Barbour-Bertotti theory, we appear to have a dilemma. Best matching comes to the rescue: by providing us with a measure of the intrinsic difference between configurations, it allows us to define a kinetic energy without recourse to time. Now, when we solve Jacobi's principle in Barbour-Bertotti theory, the orbits we obtain as solutions exactly coincide with those of Newtonian mechanics for a universe with zero total energy and zero total angular momentum. Furthermore, while Jacobi's principle dictates only the orbit and not the rate at which the orbit is traversed, Barbour-Bertotti theory allows us to derive this rate—and, consequently, the time—all from the relative distances alone. Without presupposing an absolute space or an absolute time, we have recovered Newtonian mechanics.

A key factor in Barbour-Bertotti theory is the consideration of the entire universe. This holistic approach has several important consequences. First of all, the theory yields constraints on the values of certain universal quantities, namely, the total energy and total angular momentum. A subsystem of the universe can potentially possess any value for its energy and angular momentum, but of course the remainder of the universe must counterbalance these values. This fact explains why Newtonian mechanics is fantastically accurate when applied on Earth and in the solar system; it also demonstrates that a universally relational theory can appear substantival locally. In addition to these results, Barbour-Bertotti theory dictates why time runs commensurably from system to system and how inertial reference frames emerge.

B Introduction to Intrinsic Time

In standard quantum mechanics the theory's defining equation,

$$\hat{H}\Psi = \imath\hbar\frac{\partial\Psi}{\partial t},$$

gives the time evolution of the wavefunction Ψ. This is the Schrödinger equation. $\hat{H}$ is the Hamiltonian operator, essentially the total energy of the system described by Ψ; $\imath$ is the imaginary unit; and $\hbar$ is the Planck's constant. In most cases the Hamiltonian breaks into two terms, the kinetic energy and the potential energy, respectively:

$$\hat{H}(\hat{\pi}_i, \hat{\xi}_i) = \frac{1}{2}\sum_{i=0}^{N}\hat{\pi}_i^2 + V(\hat{\xi}_i).$$

The $\hat{\pi}_i$ and $\hat{\xi}_i$ are the canonical momenta and position operators, respectively. The Schrödinger equation then reads

$$\left[\frac{1}{2}\sum_{i=0}^{N}\hat{\pi}_i^2 + V(\hat{\xi}_i)\right]\Psi = \imath\hbar\frac{\partial\Psi}{\partial t}.$$

In the position representation of quantum mechanics, we replace $\hat{\pi}_i$ with $-\imath\hbar\frac{\partial}{\partial\hat{\xi}_i}$. In this representation the Schrödinger equation becomes

$$\left[-\frac{\hbar^2}{2}\sum_{i=0}^{N}\frac{\partial^2}{\partial\hat{\xi}_i^2} + V(\hat{\xi}_i)\right]\Psi = \imath\hbar\frac{\partial\Psi}{\partial t}.$$

In the canonical approach to quantum gravity, the theory's defining equations are constraints on the universal wavefunction. This circumstance "is related to the fact that there is no possibility of studying the evolution of the system in terms of an external time."[118] The primary, or Hamiltonian, constraint of canonical quantum gravity is

$$\hat{H}\Psi = 0, \tag{1}$$

the so-called Wheeler-DeWitt equation. In all representations of this constraint produced thus far, the Hamiltonian is always quadratic in the theory's canonical momenta: the momenta enter in a sum of squares as just above.

The intrinsic time program suggests that there exists a canonical transformation T of the momentum and position coordinates,

$$\hat{\eta}_i = T(\hat{\pi}_i, \hat{\xi}_i) \qquad \text{and} \qquad \hat{\zeta}_i = T^*(\hat{\pi}_i, \hat{\xi}_i),$$

$\hat{\eta}_i$ and $\hat{\zeta}_i$ being the respective new momentum and position coordinates, such that the Hamiltonian is cast into the following form:

$$\hat{H}(\hat{\eta}_i, \hat{\zeta}_i) = \hat{\eta}_0 + \frac{1}{2}\sum_{i=1}^{N}\hat{\eta}_i^2 + V(\hat{\zeta}_i).$$

The Hamiltonian constraint then reads

$$\left[\hat{\eta}_0 + \frac{1}{2}\sum_{i=1}^{N}\hat{\eta}_i^2 + V(\hat{\zeta}_i)\right]\Psi = 0.$$

In the position representation this becomes

$$\left[-\imath\hbar\frac{\partial}{\partial\hat{\zeta}_0} - \frac{\hbar^2}{2}\sum_{i=1}^{N}\frac{\partial^2}{\partial\hat{\zeta}_i^2} + V(\hat{\zeta}_i)\right]\Psi = 0.$$

Rearranging we obtain

$$\left[-\frac{\hbar^2}{2}\sum_{i=1}^{N}\frac{\partial^2}{\partial\hat{\zeta}_i^2} + V(\hat{\zeta}_i)\right]\Psi = \imath\hbar\frac{\partial\Psi}{\partial\hat{\zeta}_0}.$$

This last equation is formally identical to the Schrödinger equation of standard quantum mechanics. According to the intrinsic time proposal, we should treat it as such, interpreting the outstanding position coordinate $\hat{\zeta}_0$ as an intrinsic time variable.

[118] [41], 252.

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