Review of Frank Arntzenius, *Space, Time, and Stuff*

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The back cover text of this excellent monograph closes with a bold remark on its methodology: "[T]he assumption that the fundamental laws of physics are simple in terms of the fundamental physical properties and relations is pivotal. Without this assumption one gets nowhere" when trying to "extract the fundamental structure of the world from theories of physics." I couldn't have put it better myself. One caveat, though: I'm not sure 'simplicity' is the best name for the cocktail of considerations appealed to here as premises. Arntzenius privileges spatiotemporally local and separable ontologies, for example, but these strike me as virtues of easy conceptual intelligibility or methodological conservatism rather than simplicity. Regardless, the reader can look forward to a marshalling of non-empirical theoretical virtues behind various alternative pictures of fundamental reality, in search of the best metaphysical explanation for some of the successes of modern physics.

Arntzenius offers no worked-out theory of simplicity and the other virtues, but here he is in good company (nearly everyone's). In cases where empirically equivalent hypotheses are on the table, we must trust that the intuitions of scientifically-trained scholars typically encapsulate a rough but reliable sense of a theory's standing with respect to theoretical virtues. Since scientists themselves carry on without any systematic picture of these virtues, theoretical science itself could not proceed without this assumption.

Could one ask for a better method? One could *ask,* I suppose, but one would have better luck asking for a pony. Given the state of the field at present, the alternatives are to give up on the sort of questions *Space, Time, and Stuff* asks, or to use something like Arntzenius's method to (tentatively) answer them. I like the way Arntzenius proceeds. The reader should just keep in mind that these are tentative conclusions with only slightly more evidential backing than opposing views.

The bulk of the book tackles several puzzles about space and time: the familiar controversy between substantivalism and relationism, the existence of instantaneous velocity, and pointless or "gunky" spaces. Arntzenius is perhaps the leading authority on the latter two topics, so as one might expect, his treatment of these issues is very rich. The discussion of substantivalism, relationism and related issues is equally rich, and notably, it largely avoids rehearsing tired thought experiments from the existing literature in favor of posing interesting new ones. For example, Arntzenius introduces the character of the "strong relationist about time," who holds that there are no temporal relations between events at different spatial locations. By examining this fascinating straw man, Arntzenius sheds considerable light on the virtues and vices of saner related positions, such as the view that there are no spatial relations between objects at different times.

This is the greatest virtue of *Space, Time, and Stuff*: the book is bursting with great material on central topics that can't be found anywhere else. It opens with a clear, minimally technical exposition of Julian Barbour's anti-realism about time, along with the methods used by Barbour (in concert with Bruno Bertotti) to formulate a "timeless" version of Newtonian physics. This is the best introductory treatment of Barbour's physics I know of, and I would advise anyone interested in this topic to begin with Arntzenius's first chapter. Chapter 7 is a foundational survey of the CPT theorem and related issues, another essential resource that was previously missing from the literature. This chapter is extremely up-to-date, and in particular it discusses the breakthrough work of Hilary Greaves and Teruji Thomas, which has not yet been published.

Some of the best chapters have more to do with the nature of matter (stuff?) than with space or time. Chapter 3, "The World According to Quantum Mechanics," is especially interesting. Rather than trying to arbitrate the old dispute about which interpretation of quantum mechanics is the best, Arntzenius picks one (the many-worlds interpretation) and asks which picture of microscopic reality is most successful, assuming that interpretation's answer to the measurement problem. While the other major interpretations are already well-understood in this regard, in many-worlds this is work that still needs doing. Unlike many other proponents of many-worlds, Arntzenius has the sensibilities of an ordinary scientific realist rather than a structural realist. So for those of us who are still scratching our heads and wondering what "structure" is supposed to mean, his approach is a welcome change of pace.

After the virtues of competing ontologies are compared, Arntzenius comes down in favor of the "Heisenberg operator realism" of Deutsch and Hayden, with Wallace and Timpson's "spacetime state realism" a close second. Both these pictures proceed by assigning fundamental quantities to regions of spacetime (represented by field operators in the former case and local density operators in the latter), in such a way that the expectation values of observables can be reconstructed as functions of these fundamental quantities. Arntzenius is judicious in comparing these ontologies to one another, but I would like to see the story of their empirical adequacy fleshed out further. I gather that his two preferred versions of the many-worlds theory are supposed to be empirically equivalent to the ordinary theory because one can derive the expectation values of observables from them. But what *is* an observable quantity like energy or momentum, on these pictures, when the fundamental quantities are just given by operators assigned to regions? And what meaning does a statistical expectation value have in the contemporary many-worlds interpretation, which is entirely deterministic and involves only a thin notion of probability (as the decision-theoretic weight rational agents will assign their successors in future branches of the universe's state)? These aren't rhetorical questions, although I think they are tough ones. I would just like to hear more.

The book closes with what may be its most significant and lasting contribution: an attempt (co-authored with Cian Dorr) to reduce all of the mathematics needed for physics to geometry alone. Although the title is "Calculus as Geometry," they do not mean to reduce calculus to the geometry of abstract mathematical spaces, but rather to the geometry of the concrete space that physical objects exist in. This approach is inspired in many ways by Field (1980), but it is not unambiguously nominalist in the same sense, since it supplements ordinary physical space with a fiber bundle over that space, which gives the possible values of gauge fields. Moreover, they freely employ mereology in their constructions. But as they point out (rightly, I think) the game need not be to satisfy some ideal of "true" nominalism. Rather, their project is to make do with less ontology than the traditional mathematical Platonist.

That said, substantivalism about the fiber bundle is a controversial assumption. Although it is probably fair to say that such substantivalism is "independently-motivated" (p. 263), it has also been the target of powerful objections, for example by Healey (2007). So we have an interesting contest between the parsimony of Arntzenius and Dorr's picture and the theoretical considerations Healey raises against fiber bundle substantivalism.

Equally interesting is their suggestion of a new, nominalist-friendly theory of quantity according to which the values of a physical quantity like mass correspond to points in "mass space," occupied by physical objects. This is perhaps best understood as a new alternative to both absolutist theories of quantity (in which values of mass are fundamental monadic properties) and comparativist theories (in which relations like "twice as massive as" are fundamental). But close analogues to the older theories will, I think, persist. For example, like the spacetime substantivalist, the realist about mass space must determine whether the points in the mass space we actually live in bear primitive relations of identity to points in other possible worlds. If so, the resulting theory will be similar to absolutism, in that the possibility where every object has twice its actual mass is a distinct possibility rather than a re-description of the actual world. Otherwise, mass space theory will be more analogous to comparativism in this regard.

Space, Time, and Stuff is ideal for the advanced reader. I wouldn't necessarily recommend it to a beginning student or someone totally unfamiliar with related literature. The book can be a little fast at some points, a little careless with details at others. I didn't find any places where the glossed-over details made a difference to the arguments, though. I had a blast reading *Space, Time, and Stuff*. Metaphysicians and philosophers of science interested in the metaphysical edge of their field will find a lot here that's genuinely new, creative and exciting. Not just about space and time. The title promises stuff, and the book delivers a lot of great stuff. I'd even go so far as to say that the stuff is the best part.

References

Field, Hartry (1980), *Science Without Numbers: A Defense of Nominalism*, Princeton: Princeton UP.

Healey, Richard (2007), *Gauging What's Real*, Oxford: Oxford UP.