1 The pyramid and the ring

A physics indifferent to ontology

Peter Galison

The credo of fundamental explanations

In the 1970s there was a confidence among particle physicists, a sense that they were on the verge of cracking the ultimate code. It is easy to understand why. Two dramatically distinct theories – one of ordinary electricity and magnetism (quantum electrodynamics), the other one of the nuclear forces (weak interaction theory) – could be subsumed under a single integrated structure. The photon carrier of light and the carriers of this nuclear force appeared to be different versions of the same thing; the new theory avoided disastrous infinities, and the first experimental confirmations were coming in right on target. Soon, the particle physicists extended this kind of theory to include what used to be called the strong nuclear force, and theorists' experimental predictions began rolling in at a fast and furious pace, on both sides of the Atlantic.

The sense that unified field theory was at last on the right track led to a breathless enthusiasm throughout the field. Within a few years, certainly by 1983, the Standard Model, as it had come to be called, was so well matched to observation that it became the background knowledge against which all other particle experiments were calibrated. At the core of this theoretical assemblage lay a few structureless, fundamental particles that carried mass, alongside a few particles that carried force. Aside from gravity, all the forces were really versions of the same thing – and the objects of the world, its fundamental constituents, could be listed in short order: a few particles like the photon, Z boson or gluon carried force, and a small number of other particles like the electron or quarks carried mass. The then elusive but now observed Higgs particle was responsible for splitting the forces at the low energies of our everyday life – cleaving electrodynamics from the weak force, for example.

It made sense for both physicists and science journalists to produce books with titles like *From Atoms to Quarks* (1980) or *Inward Bound* (1986). It became plausible to insist, as Steven Weinberg did, that even if physicists could not calculate from the fundamental theories, by dint of too much complexity, the everyday properties of biological or even ordinary materials, all questions eventually would come back to the fundamental entities and the laws that governed their interaction (Trefil 1980; Pais 1986; Weinberg 1992).Why is glass clear? Because in the visible spectrum, there are no atomic transitions to allow absorption. Why are electron orbitals what they are? Because quantum mechanics, applied to the interaction between electrons and nuclei in silica, forbid such transitions. What determines these basic interactions between electrons and nuclei? They are determined by quantum electrodynamics, a specification of the electroweak theory. Pick a problem of ordinary matter and, it appeared, a similar train of rainy-day questions will eventually drive us back to the unified quantum field theory: radioactivity, nuclear structure, chemistry, biology. This was a fundamentalism not of prediction but of explanation.

The pyramid and the ring

True, with Weinberg's interesting take on reduction, different questions would pick out different paths for the explanatory arrows, but in the end they all would converge at the pinnacle of a vast explanatory pyramid of knowledge. And if, in the 1980s, the precise form of the generalization of the electroweak theory to include the strong interactions (the totality known as the Grand Unified Theory, GUT) wasn't clear, it was imagined that it soon would be – maybe the final form would be the simplest solution of all, the 'minimal SU(5)', maybe a bit more complicated variant. If not quite in view, the peak of a single vast structure seemed to loom near, its peak hidden by clouds for now but not for long. Ending physics with a set of fundamental entities or fundamental laws or fundamental explanations sealed the deal: one more generalization of gauge theory, one more step toward finding the first of all particles, and we would be there.

Within microphysics, at least, that meant a full list of entities, an ontology coupled together with a set of laws that described the entities' fundamental interactions. By the mid-1970s, neutrinos and positrons were not only universally accepted as members of the narrow set of truly elementary particles; they had become tools. Physicists routinely used neutrino beams as probes in experiments; medical technicians used positrons to diagnose and treat disease. Sure, there were debates, but they took place at a moving edge of high energy: Was there a particle like the electron only many times heavier? Yes. Then came a third quark, then a fourth, a fifth and finally a sixth. These formed the building blocks of every nucleus: up, down, strange, charm, top and bottom. There was grumbling, of course. Condensed matter physicists, foremost Phillip Anderson, militated against the overbearing wealth and power of elementary particle physics – he disliked what he considered the disproportionate draw the particle physicists exerted over graduate students and government funding. He opposed the founding of the accelerator laboratory (Fermilab) in the early 1970s, and objected to the Superconducting Supercollider in the 1980s and 1990s. He understood early and deeply that particle physics joined its claim to temporal authority to its claim to be the branch of physics uniquely charged with the pursuit of the fundamental (Galison 1993).

Anderson's was a strong voice – a Nobel Prize winner, he eloquently and powerfully testified to Congress against the Superconducting Supercollider. His countervailing watchword was made famous in an essay of that name: 'More Is

Different' (Anderson 1972).[1] For Anderson, there are emergent phenomena, phenomena not contained in the properties of individual particles taken one by one (or one against one) altogether as 'fundamental' as anything offered by particle physics. Genuinely new things, he argued, are to be found in complex configurations of matter. Superconductivity – current flowing without any resistance in very cold conductors – was in Anderson's view a good example of something involving bulk matter that was altogether as fundamental as the way an electron scattered from a photon. For many condensed matter physicists and their philosophical allies, the universe was more quilt than quark. Fundamentality existed; it was just that fundamental fruit did not only grow in the garden of particle physics.

Looked at from afar – as is perhaps useful here – the drive to ontology has been a governing matter for a good long time. James Clerk Maxwell's followers were persuaded that the world was nothing more than a world-ether, a universe-spanning substance whose states made up all other objects (Galison 1983). Twisting, spinning, smoke-ring-like vortices of ether were really what made up charged particles. Electrical and magnetic forces, matter itself – subtract ether and you had nothing at all. Then came the Dutch theorist, Hendrik Lorentz, in many ways the first of a long sequence of charismatic theoretical physicists, who pushed for a dualistic world – ether, yes of course, but also fundamental charged particles that were not explained or built from ether. Charged particles altered the ether; the ether, in turn, told the charged particles how to move.

One or many, no- or anti-ontology?

Now, within science and within philosophy too, there has long been tradition of anti-ontology, a view that science should be more about prediction than the establishment of fundamental entities. The sixteenth-century theologian, Andreas Osiander, whether he personally believed his preface to Copernicus's *De Revolutionibus* or not, used his introduction to shift attention away from the reality of heliocentrism. The scientist-philosophers of the Vienna Circle fulminated against ontology. In fact, most of the Vienna Circle avoided any talk of ontology at all (an exception comes in the essay "Empiricism, Semantics, and Ontology" by Carnap in 1950, but that is another story). Henri Poincaré, the turn of the twentieth century French scientist-philosopher, militated for a science predicated on real relations (*'les rapports vrais'*) rather than the 'truth' of objects in and of themselves. More recent physicists too have had moments where they wanted to hold ontology at arm's length: Murray Gell-Mann, one of the physicists who introduced the world to the idea of quarks, at first clearly held them to be calculational, classificatory entities, not to be taken as physically really real; later he became persuaded that they were to be taken seriously as physical entities (Pickering 1984; Pais 1986; Gell-Mann 1994).

But whether one is aiming toward the ontological or pointing one's arrow away to avoid it, ontology has been taken to organize scientific reason. The history of physics – and its philosophical re-telling – has often been structured around an historical ontology: vacuum against plenum, phlogiston against oxygen. It has been considered necessary, even central, to pick out the building-block objects of a theory. So too is it in the social sciences. Are there groups, or are they explicable only as aggregated individuals? Are there socioeconomic classes as such that merit being considered as constituent, even fundamental objects of political economic inquiry? What, we ask when we encounter a new people or new scientific arena, is the roster of allowable entities?

I ask such questions not from some extra-historical standpoint – many of us in the broad set of science and technology studies fields have been engaged in this project. Thomas Kuhn took the paradigm to be an exemplary way of showing how ontology, nomology and epistemology were to be prosecuted by way of an example. Each paradigm carried its own ontology: Newton and the Newtonians had one set of objects; Einstein and the Einsteinians another. Indeed, nothing exemplified the paradigmatic switch better than the switch in ontology (time as absolute, for example, to relativistic time). Ian Hacking has used his notion of historical ontology to good effect. Philippe Descola returns again and again to the ontology of different cultures – of which he takes there to be four: animism, totemism, analogism and naturalism (2013). My own work on inter-languages and trading zones depends on the tracking of shared objects in the local configurations of language and action: Two scientific cultures might disagree on fundamentals, but still come to accord about a shared set of properties and dispositions for certain objects (Galison 1997).[2]

But I want here to talk about something that is happening now, something that in my view is quite unprecedented in the history of the physics: a shift not from one set of objects to another – not even a switch from the ontological to the anti-ontological (this would not be news, and in fact the anti-ontological is, of course, always ontological). No, over the last few years, something has begun to change in the sciences themselves, not toward a by-now familiar positivism, but toward what one might call the anontological: an indifference to the ontological. My claim is that a broadening set of scientific activities aims not to find out the most basic entities in the world; nor does it struggle to formulate a way to avoid such a roster of fundamental things. Not one ontology, not many ontologies, not an ontology of no ontology. Not atheism, not even agnosticism toward ontology – instead, a thoroughgoing unconcern about existence as an attribute. For emphasis, surely most circuit and app designers using global positioning technology know that their work depends on quantum mechanics and even general relativity. But if you asked them what they thought about debates over how to reconcile quantum mechanics and relativity at the edge of a black hole, I would venture that most would be, understandably, utterly indifferent. They are not withholding judgment – struggles over the 'information paradox' are, quite simply, skew to the sum total of their hardware, software, theoretical and even financial work.

I want to describe a world in which key branches of physics and related sciences no longer see the objects of their concern as a pyramid, but instead see their universe as a ring – a connected space of knowledge, but one that is connected without center.

In the middle, nanofacture – ethos of science, ethos of engineering

The mesoscopic world of nanoscience is one caught between poles. It is in just that region of sizes and energies that puts it at the boundary of macroscopic, classical physics on one side, and a small scale in which quantum physics holds well. It is a region touching the scientific at one extreme (atomic physics, surface chemistry, virology), and the much more applied (chemical, electrical and mechanical engineering) on the other. In different ways and idioms, if one distilled a common exchange, it might look like this:

CRITIC: "What you are doing is engineering not physics, drilling holes, making devices. . .these are jobs for commercial technicians not scientists."

NANO: "I want to make things, to construct devices at the smallest possible scale – a manufactured atom, an atomic-sized transistor, an instrument-probe at the atomic scale. The behavior, the manufacture of matter at the meso-scale, between quantum and classical realms, is the most interesting of all structures. I am concerned about robustness and scalability – not whether something is 'real'. Ontology is simply irrelevant to me."

For a particle physicist of the 1960s or 1970s, nothing was more important than existence questions: Did Omega Minus really exist? If it did, that meant the quark classification system was on the right track. Were weak neutral currents real, or were they nothing more than an artifact produced by ordinary and uninteresting neutrons? That early 1970s question was crucial: If they were real (produced by a heavier version of the photon), the new unified electroweak theory was truly a harbinger of a new epoch of physics. Images – bubble chamber images most strikingly – could establish existence. The omega minus bubble chamber image is an icon of physics; a senior German bubble chamber physicist waved the first image of a candidate weak neutral current electron over his head as he joined his colleagues.

Intriguingly, in the nanoscientific domain, images are still, perhaps more important than ever in the history of science. But very often the plethora of image stations in a nano-lab are not there to look, after the fact, at images in order to establish whether a new kind of entity is real. Instead, the images function in real time as part of what one might call 'nanofacture': the cutting of DNA strands or carbon nanotubes, the attachment of nanodots to other circuit elements. The nano-lab is making, altering, combining things, and imaging is a way of getting the process done. Here a conjoint ethos: making objects of genuine scientific concern and doing so within a frame of engineering.[3]

In the end there is nothing behind the screen

One sign and instance of indifference toward ontology is in the world of simulations. In the early 1950s, physicists struggled to figure out what these 'Monte Carlos' were.

Consider a simple example: To model a marble bouncing through a pinball machine, start with a position and velocity and, at regular intervals, throw a pair of dice. If a one, scatter at 60 degrees; if a 2, scatter at 120; a 3, at 180; and so on. By modeling such random events, a huge amount can be predicted about the natural world, even where no overarching theory exists.

If we numerically simulated the dispersion of a gas, was it because the random numbers used in simulations were 'like' the random collisions of molecules? That is, were numerical simulations a deeper replication of stochastic phenomena in the world than deterministic theory could ever be? Or, as others argued, were these simulations like experiments, where different tries would never quite generate the same result? For quite some time, many physicists and astrophysicists thought of these simulations as something preliminary, a surface solution that would only be completed through the deeper considerations of analytic theory that alone could truly bring 'understanding' (Galison 1997). Such Monte Carlo methods spread (e.g., calculating integrals by randomly sampling the value of a function) to a very wide range of domains – from chemistry and nuclear physics to the calculation of galaxy formation and fluid dynamics.

But the intrusion of such numerical simulations into the heartland of the physical sciences also carried with it a long-term battle, in part generational, that marked a shift from seeing simulations as an indication but not true science – to the pragmatic attitude that counts simulation as a way of reaching a goal. Again, if one imagined the following idealized exchange between critic and defender, it might go like this:

CRITIC: "All you simulators have done is preliminary – real physics is to show just the term in the physical law that explains what has happened. Only then can we point to a term in the equation and say *that* is the real cause of the phenomenon in question."

SIMULATOR: "If we can start with Newton's inverse square law and some simple assumptions about the distribution of matter, and if we can show that the galaxies in fact do form into a spiral or lens shape by means of a simulation using a Monte Carlo, then we are done! We have shown that some basic processes, repeated over and over, produce one of the great and dominant visible structures of our universe. All your analytic techniques are just antiques, a poor man's crutch useful before computers, but hardly the sacred core of science. We simulators are interested in prediction, in deriving structures through calculation. But we are utterly indifferent to whether the Monte Carlo calculational processes capture the reality of the phenomena. I want the results to match what we see through our telescopes. Whether the world is random in just the way that my pseudo-random number generator is random simply does not matter. I am indifferent to the ontology of the elementary bits along the way. I do not care at all if it is possible, in some labored and far future mathematical inquiry, to find an analytical solution. Ontology is irrelevant.

In the beginning, there is no beginning

At first, string theory seemed to promise the pyramid of all pyramids: an account that would unify beyond the wildest expectations of the most ambitious particle physicists. The latter had wanted to show that the weak, the strong and the electrodynamics forces all derived from a single 'ur-force'. The photon, gluons, the W and the Z were just low energy recombinations of a more originary set of force-carrying particles. String theory promised more. Instead of thirty or so free parameters, string theory would offer none – a theory so constrained by mathematical consistency that there was nothing left to be fixed by experimental knowledge. String theory would join gravity to particle physics and end the historical project of inquiry into the building blocks nature. In the beginning, so the answer would go, there were extended, one-dimensional objects held under a tension producing load of some 10*39 tons, whose excited states constituted the particles that for decades we have taken as fundamental.

For this project to work, there would have to be a law of physics, *the* law of physics. And for a time – from what physicists called the first string revolution in 1984 through the second revolution of 1995 and even a few years beyond – it seemed possible. As Weinberg insisted in many places, one day physicists could wake up to find that someone had actually written down the right Lagrangian – the law governing the physics of strings. And from that law (it was hoped) would come all else: the masses, charges and other characteristics of the electron and its heavier relatives, neutrinos, quarks and the particles that bound them together. From those objects could, in principle (as the saying goes), be derived the features of chemistry, biology, planets, solar systems and galaxies.

It is not that string theory had been unopposed. Experimentalists had long derided it for its lack of contact with laboratory results. 'Theology', Sheldon Glashow called it, better studied on Divinity Avenue than in the Jefferson Physics Laboratory. String theorists responded that this was in fact science, constrained it was true not by accelerator results but by mathematical self-consistency. Even theoretical particle physics blasted the theory – for people like Howard Georgi, string theory had lost the back and forth between theoretical ideas and experimental results that had made gauge theory so successful back in the 1970s. No physical theory – no scientific theory – had ever achieved the remarkable correspondence between prediction and result that gauge theories had provided. Why give up this happy collaboration? Ah, the string theorists responded, good science was not always done in this way – think of Einstein ferreting out the equations of relativistic gravity with no more to go on than the precession of the perihelion of Mercury. Should Einstein have given up because he couldn't match results with his pals in the precision laboratories?

But now, in these last few years, comes a third stance toward string theory because it has become clear that even if there is a single governing set of equations – the world equation – there are a lot of solutions. A vast amount of solutions – on the order, some estimate of 10^{100} solutions (a googol) maybe more. The question then arises: Which one is ours? Imagine a hugely complex system of mountains where every valley, peak, or inflection point represents a solution. Every one picks out a particular set of particles and forces. Which is our universe? Maybe there's a principle that would pick out ours, but maybe there isn't. It is this latter possibility that has split the string theory community itself right down the middle – right down the Continental Divide in the United States, with many of the West Coast physicists opting for what has been called the landscape and the East Coast lobbying hard against it.

Here's the idea

String theorists hoped to have one equation and one solution; instead they got many with no selection principle on the basis to choose our real universe's actual values of things like the ratio of the electron to the proton. Maybe, say the anthroposophs, all of the possible solutions are, in fact, realized. Now most all of them could not support galaxies, could not make higher elements and in particular could not generate life – and us. "So what?" they say. We have the right values of the ratio of the mass of the electron to the mass of the proton (e/p) not because anyone or anything made them for us but because all the possible values of e/p are in fact in use, and our presence in the universe means we live in a universe where a value of e/p allows life. After all, are you surprised that your great grandparents all survived the flu pandemic of 1918? You shouldn't be. If they hadn't, you wouldn't be here. Are you surprised that we live in one of the solution spaces that include electrons and protons that are compatible with life? *Mutatis mutandis* – you shouldn't be.

Now the anthroposophs have enemies. The East Coast of the Continental Divide, with some West Coast allies, detests this form of us-centered argumentation. Ed Witten of the Princeton Institute for Advanced Study finds the prospect of such anthropic account exceedingly depressing; so does his colleague Juan Maldecena, Harvard's Andrew Strominger and many others. Stanford, by contrast, is anthropic HQ: Leonard Susskind, also one of the founders of string theory, along with his colleagues Andre Linde (known for his work on cosmic inflation) and particle phenomenologist and model builder Savas Dimopoulos, all see the anthropic turn as an incipient scientific revolution of the first order.

David Gross, director of the Kavli Institute for Theoretical Physics (Santa Barbara) puts himself into the Pacific Time Zone's column of resistance: he sees the effort as, in the first instance, not physics. "Look," he says, "imagine we were back in 1940, facing the theoretical mess and sprawling disconnected data associated with nuclear physics." We could well be thinking that the myriad nuclear structure relations were miraculously tuned to make life possible. Someone clever could easily have invoked the anthropic principle to explain these fortuitous relations. But they aren't fortuitous at all, at least not at the level of nuclear physics; they are the explicable consequence of a deeper, underlying theory that explains what the protons and neutrons are and how they bind together. That theory – the theory of quarks and their glue, the 'gluons' – arose thirty or so years later: quantum chromodynamics. Why not expect something of this order with string theory? Sure, we do not know what it might be yet, but why throw in the towel because we can't solve the problem (Gross 2008)?

In July 2005, all the key leaders of string theory gathered for a major meeting (Shenker 2005), and no topic was as hotly contested as the anthropic principle. One after another, the lead panel weighed in – and split their judgment down the middle, four against four. Then Steve Shenker addressed the question to the very large audience. "I want to ask you I guess as a snap question: Do you think that the smallness of the cosmological constant will be explained by the anthropic principle or by a physical principle? That there will be a large landscape and . . . it will rely on some sort of environmental variable?" (Andy Strominger interjected: "We're talking about the year 3000!"). The audience voted, and Shenker exclaimed, "Wow, holy shit! 5:1 for a physical explanation! . . . That's it. The anthropic principle is out of office!" He then asked, "How many people think God made the universe just for us?" Very few hands went up. Then someone from the audience said, "I think God made the landscape" (Shenker 2005).

On the anthropic side there is clearly a putting aside of the original hope for a theory that would offer the one true answer to what there was in the universe. Intriguingly, even among those who are not particularly sympathetic to the anthropic program and who are optimistic about string theory, there is a growing sense that the claims for a 'theory of everything' were overblown. Strominger, for example, has great hopes for string theory – he thinks that we will, in fact, come to understand many of the current puzzles about the theory. But he does not think that string theory now – or in the future – is all of physics. Instead, he sees it as a fascinating corner of the field, one that will productively deepen both our understanding of quantum field theory and of the deepest mathematical structures.[4]

Strominger's view – that string theory was a generative 'corner of the field', but hardly the end of physics, has become increasingly a view even of those who reject the anthropic assault on the fundamentalist position. John McGreevy, a theorist at MIT, takes as his starting point the idea that there are two ways to advance and connect string theory with the rest of physics. One is to use string theory to look at the smallest possible distances, and then to use the results to explain very basic problems of physics (e.g., Does the topology of spacetime change?). When advanced students at MIT come to his class on 'applied string theory', however, they learn through another approach, one increasingly in favor among physicists: use of a relation discovered in string theory, called the 'holographic principle' (or more technically AdS/CFT), that shows two theories can be equivalent – one in a higher dimension and the other essentially defined as a kind of projection onto its boundary.

Here's how McGreevy's class began in the fall of 2008:

> So here's my crazy plan: we will study the AdS/CFT correspondence and its applications and generalizations, without relying on string perturbation theory.
>
> Why should we do this? You may have heard that string theory promises to put an end once and for all to that pesky business of physical science. Maybe

> something like it unifies particle physics and gravity and cooks your breakfast. Frankly, in this capacity, it is at best an idea machine at the moment.
>
> But this AdS/CFT correspondence, whereby the string theory under discussion lives not in the space in which our quantum fields are local, but in an auxiliary curved extra-dimensional space . . . is where string theory comes the closest to physics. . . .The role of string theory in our discussion will be like its role in the lives of practitioners of the subject: a source of power, a source of inspiration, a source of mystery and a source of vexation.
>
> (McGreevey 2008)[5]

Actually doing string theory, in McGreevy's view, is not about the hunt that once seemed to be closing in on its quarry: a single, final equation that provided the last station of the physicists' two thousand-year-old voyage toward the innermost, deepest fundamental level of physical reality. Instead, the view that is emerging is that string theory has led to a series of mathematical clues. Among these are the linking principles, like the 'holographic principle', which says that theories can be equivalent, even if one looks enormously different from the other. Here is a theory that says we can learn about gravity, black hole entropy and much else besides by looking at the very 'ordinary', experimental phenomena of condensed matter physics, or the hitting of one big fat ion against another in accelerators like the one at Brookhaven – seemingly far from the cutting edge of CERN, much less the staggering energies one would think necessary to look at string theory directly.

Applied string theory is an account of physics that links domains, but not by solving things at the 'most fundamental' and then deriving reality down the food chain: quarks and leptons, nuclei, atoms, molecules, ordinary matter, people, worlds and galaxies. Our slogan recurs: fields linked, but not hierarchically. What is surprising is that it recurs at the heart of a long tradition that just about defined the ontological lineage of modern science: molecules, atoms, nuclei, nucleons, quarks, strings. So here again, imagine an idealized exchange of the type we fastened on earlier. The first, without exaggeration, is precisely the kind of exchange that occurred in the mid-1980s; the others draw from more recent struggles (Galison 1995).

CRITIC: "Physics without experiment is theology, not science."

STRINGER (CA. 1985): "No! Physics without experiment is constrained by mathematical consistency. Maths is the new experiment."

CRITIC: "Physics that justifies itself by mathematical yield is not science; it has abandoned the historical mission of hunting for fundamental entities."

STRINGER (2010s): "No! String theory is one science among others, with the mission of building structures that offer insight into both physics (at a variety of scales) and a wide swath of mathematics from algebraic geometry to knot theory."

CRITIC: "Physics that does not predict, that relies on evolutionary explanation is not physics."

STRINGER (LANDSCAPE VARIETY): "No! Like Darwin, this is a new and revolutionary modesty, knowing when not to explain is just as important as knowing what to explain. And even if we want physical laws all the way down, so to speak, they bear relations of duality, not hierarchical ordering to a range of other parts of physics, from condensed matter to heavy ions smashing into a quark soup at accelerators around the world."

An engineering way of being within the sciences

We are used to thinking of a fight to the finish between two positions grounded at the intersection of physics and philosophy. On the one side is an absolute fundamentalism that grounds the connectedness (unity) of science in a hierarchically centered world that imagined a pyramid, with atoms or elementary particles or strings at the high center. This view captures very well the enormous weight put upon the discovery of specific objects – indeed we celebrate and periodize the discovery of the electron, the neutron, the quarks, the particulate photon and a host of other entities just because the building-block picture of the sciences is so alluring.

On the other side stands a rebellious alternative that sets many disciplinary domains as equal, each just as valid as the other, but disconnected, more a quilt with weak stitching than a pyramid. Here, scientists and philosophers emphasize emergence not reduction; they seek to establish the ontological autonomy of different domains based on complexity, life or laboratory methods.

But what may be emerging in the twenty-first century – and I am by no means insisting that everyone subscribes to this view – is an image of science skew to the perpetual oscillation between fundamentality and autonomy. It is a view that differs from fundamental ontology because it refuses a center. But it simultaneously differs from the autonomy (quilt or island) view because it holds a wide variety of sciences to be connected, though without a governing core. A focus on novel effects, materials, and objects, but constructed through an engineering way of being that values the making and linking of structures with little regard for the older fascination with existence for its own sake. We may be witnessing the arrival of a different kind of science, inflected by making but deeply imbricated in the sciences: linked sciences, but formed into a ring by a broad and expanding consensus leaves the pyramidical hierarchy in the sands of Giza.

Notes

1 See also U.S. Congress, Senate, *Joint Hearing before the Committee on Energy and Natural Resources and the Subcommittee on Energy and Water Development, Importance and Status of the Superconducting Supercollider*, 102nd Cong., 2nd Sess., June 30, 1992.

2 For more on trading zones, see, e.g., Strübing et al. (2004), Gorman (2010) and Balducci and Mäntysalo (2013).

3 For more on this argument, see Daston and Galison (2007), especially ch. 7.

4 Overbye (2005) reports on theorists trying democracy by voting with a 4:4 split on the panel and the audience voting overwhelmingly for the non-anthropic principle. On the panel were Raphael Bousso (UC Berkeley), Shamit Kachru (SLAC & Stanford), Ashok Sen (Harish-Chandra Research Institute), Juan Maldacena (IAS, Princeton), Andrew Strominger (Harvard), Joseph Polchinski (KITP & UC Santa Barbara), Eva Silverstein (SLAC & Stanford) and Nathan Seiberg (IAS, Princeton).

5 The reason: it offers otherwise-unavailable insight into strongly coupled field theories (examples include QCD in the infrared, high-temperature superconductors, cold atoms at

unitarity) and into quantum gravity (questions about which include the black-hole information paradox and the resolution of singularities), and through this correspondence, gauge theories provide a better description of string theory than the perturbative one.

References

Anderson, P. W. 1972. 'More is different: Broken symmetry and the nature of the hierarchical structure of science.' *Science* 177 (4047): 393–396.

Balducci, A. and Mäntysalo, R. (eds.). 2013. *Urban Planning as a Trading Zone*. Heidelberg, New York and London: Springer.

Carnap, R. 1950. 'Empiricism, semantics, and ontology.' *Revue Internationale de Philosophie* 4: 20–40.

Daston, L. and Galison, P. 2007. *Objectivity*. New York: Zone Books.

Descola, P. 2013. *Beyond Nature and Culture*. Chicago: University of Chicago Press.

Galison, P. 1983. 'Re-Reading the Past from the End of Physics: Maxwell's Equations in Retrospect.' *Functions and Uses of Disciplinary Histories*, edited by Graham, L., Lepenies, W. and Weingart, P., 35–51. Dordrecht: Kluwer.

———. 1993. 'Metaphysics and Texas.' Review of *Dreams of a Final Theory* by S. Weinberg, *The New Republic* 6 (September): 41–42.

———. 1995. 'Theory Bound and Unbound: Superstrings and Experiment.' In *Laws of Nature: Essays on the Philosophical, Scientific and Historical Dimensions*, edited by Weinert, F., 369–408. Berlin and New York: Walter de Gruyter.

———. 1997. *Image and Logic: A Material Culture of Microphysics*. Chicago: University of Chicago Press.

Gell-Mann, M. 1994. *The Quark and the Jaguar: Adventures in the Simple and the Complex*. New York: W.H. Freeman and Co.

Gorman, M. E. (ed.). 2010. *Trading Zones and Interactional Expertise: Creating New Kinds of Collaboration*. Cambridge: MIT Press.

Gross, D. 2008. 'Einstein and the Quest for a Unified Theory.' In *Einstein for the 21st Century: His Legacy in Science, Art, and Modern Culture*, edited by Galison, P., Gerald Holton, L. and Schweber, S. S., 287–298. Princeton: Princeton University Press.

McGreevey, J. 2008. Notes from class at MIT: 8.821 (Fall), http://web.mit.edu/~mcgreevy/www/fall08/index.html.

Overbye, D. 2005. 'Lacking hard data, theorists try democracy.' *New York Times*, 2 August, http://www.nytimes.com/2005/08/02/science/lacking-hard-data-theorists-try-democracy.html (accessed October 22, 2016).

Pais, A. 1986. *Inward Bound: Of Matter and Forces in the Physical World*. Oxford: Clarendon Press.

Pickering, A. 1984. *Constructing Quarks: A Sociological History of Particle Physics*. Chicago: University of Chicago Press.

Shenker, S. 2005. The Next Superstring Revolution Panel Discussion. Toronto Strings 12 July 2005, http://www.fields.utoronto.ca/audio/05–06/strings/discussion.

Strübing, J., Schulz-Schaeffer, I., Meister, M. and Gläser, J. (eds.). 2004. *Kooperation im Niemandsland: Neue Perspektiven auf Zusammenarbeit in Wissenschaft und Technik*. Opladen: Leske & Budrich.

Trefil, J. S. 1980. *From Atoms to Quarks: An Introduction to the Strange World of Particle Physics*. New York: Scribner.

Weinberg, S. 1992. *Dreams of a Final Theory: The Scientist's Search for the Ultimate Laws of Nature*. New York: Pantheon.