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Bioconstructivisms

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Abstract
On meeting the German structural engineer Frei Otto in 1998, Lars Spuybroek was struck by the extent to which Otto's approach to the design of light structures resonated with his own interest in the generation of complex and dynamic curvatures. Having designed the Freshwater Pavilion (1994-97) using geometric and topological procedures, which were then materialized through the exigency of a steel structure and flexible metal sheeting, Spuybroek found in Otto a reservoir of experiments in developing curved surfaces of even greater complexity by means of a process that was already material- that was, in fact. simultaneously material, structural and geometric. Moreover. Otto's concem with flexible surfaces not only blurred the classic distinctions between surface and support, vault and beam (suggesting a non-elemental conception of structural functions) but also made construction and structure a function of movement or, more precisely, a function of the rigidification of soft, dynamic entities into calcified structures such as bones and shells. Philosophically inclined towards a dynamic conception of the universe - a Bergsonian and Deleuzian ontology of movement, time and duration - Spuybroek embarked on an intensive study of Otto's work and took up his analogical design method. A materialist of the first order, Spuybroek now developed his own experiments following those of Otto with soap bubbles, chain nets and other materials as a way to discover how complex structural behaviours find forms of their own accord, which can then be reiterated on a larger scale using tensile, cable or shell constructions.

Disciplines
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Comments
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On meeting the German structural engineer Frei Otto in 1998, Lars Spuybroek was struck by the extent to which Otto's approach to the design of light structures resonated with his own interest in the generation of complex and dynamic curvatures. Having designed the Freshwater Pavilion (1994–97) using geometric and topological procedures, which were then materialized through the exigency of a steel structure and flexible metal sheeting, Spuybroek found in Otto a reservoir of experiments in developing curved surfaces of even greater complexity by means of a process that was already material – that was, in fact, simultaneously material, structural and geometric. Moreover, Otto's concern with flexible surfaces not only blurred the classic distinctions between surface and support, vault and beam (suggesting a non-elemental conception of structural functions) but also made construction and structure a function of movement or, more precisely, a function of the rigidification of soft, dynamic entities into calcified structures such as bones and shells. Philosophically inclined towards a dynamic conception of the universe – a Bergsonian and Deleuzian ontology of movement, time and duration – Spuybroek embarked on an intensive study of Otto's work and took up his analogical design method. A materialist of the first order, Spuybroek now developed his own experiments following those of Otto with soap bubbles, chain nets and other materials as a way to discover how complex structural behaviours find forms of their own accord, which can then be reiterated on a larger scale using tensile, cable or shell constructions.

This curious encounter between Spuybroek and Otto sends us back not only to the 1960s, but deeper in time. The recent re-engagement of architecture with generative models from nature, science and technology is itself part of a longer history of architects, engineers and theorists pursuing autopoiesis, or self-generation. While its procedures and forms have varied, self-generation has been a consistent goal in architecture for over a century, set against the perpetuation of predetermined forms and norms. The well-known polemic of the early twentieth-century avant-garde against received styles or compositional systems in art and architecture – and against style per se – may, in fact, be understood as part of a longer and larger shift in thought from notions of predetermination to self-generation, transcendence to immanence. The search for new methods of design has been integral to this shift, whether it be figured in terms of a period-setting revolution or the immanent production of multiplicity. Although a history of generative architecture has yet to be written, various partial histories in art, philosophy and science may serve to open this field of research.

In his landmark cross-disciplinary study, *Self-Generation: Biology, Philosophy and Literature around 1800* (1997), Helmut Müller-Sievers describes how the Aristotelian doctrine of the epigenesis of organisms – having been challenged in the seventeenth century by the rise of modern sciences – resurfaced in the eighteenth century, as the mechanistic theories of Galileo, Descartes and Newton foundered in their explanations of the appearance of new organisms. Where figures such as Charles Bonnet and Albrecht von Haller held that the germs of all living beings had been preformed since the Creation – denying nature any productive energy – a new theory of self-generation gradually took shape. An active inner principle was first proffered by the Count de Buffon and then elaborated by Caspar Friedrich Wolff, explaining the production of new organisms through the capacity of unorganized, fluid material to consolidate itself. Johann Friedrich Blumenbach transformed Wolff's 'essential force' into a 'formative drive' that served as the motive for the successive self-organization of life forms, understanding this as a transition from unorganized matter to organized corporations.[1] The biological theory of epigenesis came to underpin the theory of autonomy in the human sphere – in art, aesthetics, philosophy, politics and social institutions such as marriage. As Müller-Sievers has noted, Blumenbach's epigenesis provided a direct model for Kant's deduction of the categories, on which his shift from metaphysics to epistemology relied: 'Only if they are self-produced can the categories guarantee transcendental apriority and, by implication, cognitive necessity and universality'.[2]

In a similar vein, but looking to mathematics and its influence, rather than biology or aesthetics, the philosopher David Lachterman characterized the whole of modernity as 'constructivist' and traced its origins further back to the shift in the seventeenth century from ancient to modern mathematics. Where the mathematics of Euclid focused on axiomatic methods of geometric demonstration and the proof of theorems (existence of beings), modern mathematics emphasized geometrical construction and problem-solving.[3] As Lachterman put it, a fairly direct line runs from the 'construction of a problem' in Descartes through the 'construction of an equation' in Leibniz to the 'construction of a concept' in Kant.

Rather than reiterating ontologies of sameness, modern mathematics produced difference through new constructions. In this regard it is telling that, as Lachterman points out, Euclidean geometry arose against a Platonic backdrop that understood each of the mathematicals as having unlimited manyness. According to the doctrine of intermediates, 'the mathematicals differ from the forms inasmuch as there are many "similar" [*homoia*] squares, say, while there is only one unique form.' Lachterman continues: 'The manyness intrinsic to each "kind" of figure as well as the manyness displayed by the infinitely various images of each kind must somehow be a multiplicity indifferent to itself, a manyness of differences that make no fundamental difference, while nonetheless never collapsing into indiscriminate sameness or identity with one another.'[4] A Euclidean construction, then, does not produce heterogeneity, but rather negotiates an intricate mutuality between manyness and kinship, variation and stability. It is always an image of this one, uniquely determinate specimen of the kind. 'There is no one perfect square, but every square has to be perfect of its kind, not *sui generis*.'[5]

The quest for autopoiesis has been expressed, then, in a variety of oppositional tropes – creation versus imitation, symbol versus rhetoric, organism versus

1. See Helmut Müller-Sievers. *Self-Generation: Biology, Philosophy and Literature around 1800* (Stanford: Stanford University Press, 1997).

2. Ibid: 46.

3. David Rapport Lachterman. *The Ethics of Geometry: A Genealogy of Modernity* (New York and London: Routledge, 1989): vii.

4. Ibid: 117–18.

5. Ibid: 118.

mechanism, epigenesis versus preformation, autonomy versus metaphysics and construction *sui generis* versus reiteration of forms. In the nineteenth century, such binary oppositions came to underpin the quest for freedom among the cultural avant-garde. In his *Five Faces of Modernity* (1987), Matei Calinescu recounted that the term 'avant-garde' was first introduced in military discourse during the Middle Ages to refer to an advance guard. It was given its first figurative meaning in the Renaissance, but became a metaphor for a self-consciously advanced position in politics, literature and art only during the nineteenth century. In the 1860s, Charles Baudelaire was the first to point to the unresolved tension within the avant-garde between radical artistic freedom and programmatic political campaigns modelled on war and striving to install a new order – between critique, negation and destruction, on the one hand, and dogma, regulation and system, on the other. An alternative interpretation of what Calinescu calls the *aporia* of the avant-garde – one that sharpens the implications of this problematic, both philosophically and politically – is suggested by Michael Hardt and Tony Negri's account of the origins of modernity in their book, *Empire* (2000). Their history is even more sweeping than those reviewed above, summarizing how, in Europe between 1200 and 1400, divine and transcendental authority over worldly affairs came to be challenged by affirmations of the powers of this world, which they call 'the [revolutionary] discovery of the plane of immanence'. Citing further evidence in the writings of Nicholas of Cusa among others, Hardt and Negri conclude that the primary event of modernity was constituted by shifting knowledge from the transcendental plane to the immanent, thereby turning knowledge into a doing, a practice of transform-ing nature. Galileo Galilei went so far as to suggest that it was possible for humanity to equal divine knowledge (and hence divine doing), referring specifically to the mathematical sciences of geometry and arithmetic. As Lachterman suggested using somewhat different terms, on the plane of immanence, mathematics begins to operate differently from the way it operates within philosophies of transcendence where it secures the higher order of being. On the plane of immanence, mathematics is done constructively, solving problems and generating new entities. For Hardt and Negri, 'the powers of creation that had previously been consigned exclusively to the heavens are now brought down to earth.'

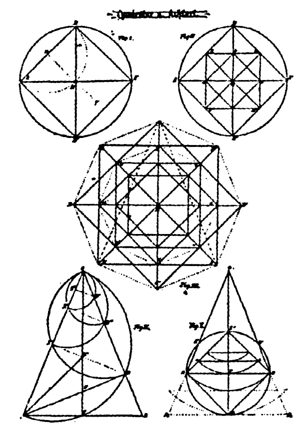
By the time of Spinoza, Hardt and Negri note, the horizon of immanence and the horizon of democratic political order had come together, bringing the politics of immanence to the fore as both the multitude, in theoretical terms, and a new democratic conception of liberation and of law through the assembly of citizens.[6] The historical process of subjectivization launched an immanent constitutive power and, with it, a politics of difference and multiplicity. This in turn sparked counterrevolutions, marking the subsequent history as 'an uninterrupted conflict between the immanent, constructive, creative forces and the transcendent power aimed at restoring order'.[7] For Hardt and Negri, this crisis is constitutive of modernity itself. Just as immanence is never achieved, so the counterrevolution is also never assured.

The conflict between immanence and transcendence may also be discerned in architecture, along with efforts to resolve it through the mediation of an architectonic system for free expression or self-generation. Critical of using historical styles, which were understood as residual transcendent authorities no longer commensurate with the present, progressive architects of the early twentieth century sought to develop a modern style that, in itself, would also avoid

6. Michael Hardt and Antonio Negri. *Empire* (Cambridge, MA: Harvard University Press, 2000): 73.

7. Ibid: 77.

the problem of predetermination, which had taken on new urgency under the conditions of industrialization and mass production. Such a style was conceived more in terms of procedures than formal idioms. For instance, in a piece of history that has received inadequate attention, a number of Dutch architects around 1900 turned to proportional and geometric constructions as generative tools. Recognizing that not only classical, but also medieval and even Egyptian architecture employed proportional systems and geometric schema, they hoped to discover a universal mathesis, both timely and timeless, for a process of design whose results were not already determined at the outset. The validity and value of such forms were guaranteed, it was thought, by virtue of the laws of geometry, whose own authority was, in turn, guaranteed by their giveness in nature. Foremost among a group that included J. H. de Groot, K. P. C. de Bazel, P. J. H. Cuypers, and J. L. M. Lauweriks, was H. P. Berlage, whose celebrated Stock Exchange in Amsterdam (1901) was based on the Egyptian triangle.



H. P. Berlage. Diagrams of quadrature (*The Western Architect*, 19, 1912).

In lectures and publications of around 1907 – synopses of which were translated and published in America in 1912 – Berlage articulated his theory of architecture based on the principles and laws of construction. Taking issue with the growing pluralism of taste-styles, he sought an objective basis for design – including the peculiarities of construction and the arrangement of forms, lines, and colours – in the laws of nature. He described these as 'the laws under which the Universe is formed, and is constantly being reformed; it is the laws which fill us with admiration for the harmony with which everything is organized, the harmony which penetrates the infinite even to its invisible atoms.'[8] He went on to argue that adherence to nature's laws and procedures need not lead to mindless repetition and sameness, since nature produces a boundless variety of organisms and creatures through the repetition of basic forms and elements. Similarly, he considered music a paradigm, since here too creativity appeared unhampered in the adherence to laws. Citing Gottfried Semper, Berlage extended this analogy to suggest that even evolution is based on 'a few normal forms and types, derived from the most ancient traditions'. They appear in an endless variety that is not arbitrary but determined by the combination of circumstances and proportions, by which he meant relations or, more precisely, organization. For Berlage, this led directly – for both practical and aesthetic reasons – to mathematics in art as in nature. He wrote:

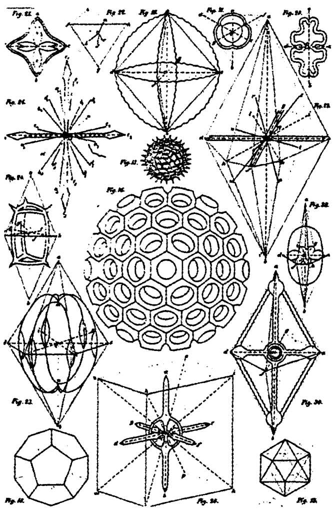
8. H. P. Berlage. 'Foundations and Development of Architecture (Part 1)'. *The Western Architect* (vol. 18, no. 9, September 1912): 96–99. Part 2 (vol. 18, no. 10, October 1912): 104–08. These articles were based on his *Grundlagen der Architektur* (Berlin: Julius Bard, 1908), which compiled five illustrated lectures delivered at the Kunstgewerbe Museum in Zurich in 1907.

> I need only remind you in this connection of the stereometric–ellipsordic forms of the astral bodies, and of the purely geometrical shape of their courses; of the shapes of plants, flowers and different animals, with the setting of their component parts in purely geometrical figures; of the crystals with their purely stereometrical forms, even so that some of their modifications remind one especially of the forms of the Gothic style; and lastly, of the admirable systematicalness of the lower animal and vegetable orders, in latter times brought to our knowledge by the microscope, and which I have myself used as motive for the designs of a series of ornaments.[9]

9. Berlage. 'Foundations' (Part 1): 97.

It is worth noting that, as Berlage was putting forward a constructivist cosmology of architecture, Peter Behrens in Germany drew on some of the same proportional systems but with a more conservative agenda, reiterating the transcendent claims of classicism through a neo-Kantian schematism. For Behrens, geometry constituted an a priori architectonic system that was to be applied across buildings, landscapes and furniture to raise the material world to the higher plane of *Kultur*, while for Berlage architecture was based on a living geometry, in itself heterogeneous rather than homogeneous, with which to produce novel astylar forms that belonged to this world.[10] Behrens's pursuit of the 'great form' – symbol of the transcendence of pure mind and spirit – privileged architectonics over construction and maintained a clear hierarchy between the material and the ideal. In contrast, for Berlage architecture was at once geometric, material, technological and biological. He understood beauty to be immanent to the self-actualization of material entities, contingent only on the rational (*sachlich*) use of means and the laws of geometry.

10. H. P. Berlage. *Grundlagen der Architektur* (Berlin: Julius Bard, 1908): 7, 16, 38–39.



Basic polyaxon and homopolar forms. Plate II in Ernst Haeckel, *Generelle Morphologie der Organismen* (vol. 1, 1866).

In citing the 'admirable systematicalness of the lower animal and vegetable orders', Berlage alluded to the microscopic single-cell sea creatures studied by the German zoologist Ernst Haeckel in the 1880s and popularized in his book of 1904, *Kunstformen der Natur [The Art Forms of Nature]* as well as other writings, including his *Report of the Scientific Results of the Voyage of H.M.S.* Challenger (London, 1887), which was later often cited. Haeckel estimated that there were 4,314 species of radiolarian included in 739 genera found all over the world, without any evident limitations of geographical habitat.[11] He also noted that the families and even genera appear to have been constant since the Cambrian age. This uni-cellular species of organisms became an exemplar for those interested in learning from the way in which self-generation in nature could produce seemingly endless variety – if not multiplicity per se – in complex as well as simple forms of life. Haeckel hoped that knowledge of Ur-animals (protozoa such as radiolarians, thalamophorians and infusorians) and Ur-plants (protophntoa such as diatomians, rosmarians and veridienians) 'would open up a rich source of motifs for painters and architects' and that 'the real art forms of Nature not only stimulate the development of the decorative arts in practical terms but also raise the understanding of the plastic arts to a higher theoretical level.'[12]

In his own landmark book, *On Growth and Form* (1917), the Scottish biologist D'Arcy Wentworth Thompson developed science's understanding of form in terms of the dynamics of living organisms, their transformation through growth and movement.[13] In considering the formation of skeletons, he recounted Haeckel's theory of 'bio-crystallization' among very simple organisms, including radiolarians and sponges. While the sponge-spicule offered a simple case of growth along a linear axis – their skeletons always begin as a loose mass of isolated spicules – the radiolarians provided a more complex case among single-cell organisms, exhibiting extraordinary intricacy, delicacy and complexity as well as beauty and variety, all by virtue of the 'intrinsic form of its elementary constituents or the geometric symmetry with which these are interconnected and arranged'.[14] For Thompson, such 'biocrystals' represented something 'midway between an inorganic crystal and an organic secretion'.[15] He distinguished their multitudinous variety from that of snowflakes, which were produced through symmetrical repetitions of one simple crystalline form, 'a beautiful illustration of Plato's *One among the Many*'.[16] The generation of the radiolarian skeleton, on the other hand, is more complex and open-ended, for it 'rings its endless changes on combinations of certain facets, corners and edges within a filmy and bubbly mass'. With this more heterogeneous technology, the radiolarian can generate continuous skeletons of netted mesh or perforated lacework that are more variegated, modulated and intricate – even irregular – than any snowflake.[17]

11. Ernst Haeckel. *Report of the Deep-Sea Keratosa [collected by H.M.S.* Challenger *during the years 1873–76]* (London: Eyre & Spottiswoode, 1889): clxxxviii.

12. Ernst Haeckel. *Kunstformen der Natur* (Leipzig and Vienna: Verlag des Bibliographischen Instituts, 1904). Translation by author.

13. D'Arcy Wentworth Thompson. *On Growth and Form* (New York: Dover, 1992). Published originally in 1917 and revised in 1942.

14. Ibid: 645.

15. Ibid: 691.

16. Ibid: 695.

17. Ibid: 698.

For enthusiasts of biocrystallization, one of the key features of radiolarians was the apparently perfect regularity of their form or, more precisely, of their skeleton and the outer surface layer of froth-like vesicles, 'uniform in size or nearly so', which tended to produce a honeycomb or regular meshwork of hexagons. The larger implications of this regularity were made explicit in scientific cosmologies of the early-twentieth century, such as Emmerich Zederbauer's *Die Harmonie im Weltall in der Natur und Kunst* (1917) and Ernst Mössel's *Vom Geheimnis der Form und der Urform des Seines* (1938). Supported by the evidence of ever more powerful microscopes and telescopes, these authors sought to confirm that the entire universe was ordered according to the same crystalline structural laws – establishing continuity from the structure of molecules and microscopic radiolarians to macroscopic celestial configurations, between organic and inorganic, nature and technology.

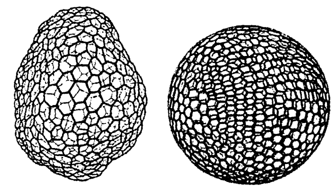


Fig. 321. "*Reticulum plasmatique.*" After Carnoy. Fig. 322. *Aulonia hexagona* Hkl.

Two radiolarians, the *Reticulum plasmatique*, after Carnoy, and the *Aulonia hexagona*, as depicted by Haeckel. D'Arcy Thompson, *On Growth and Form* (1942).

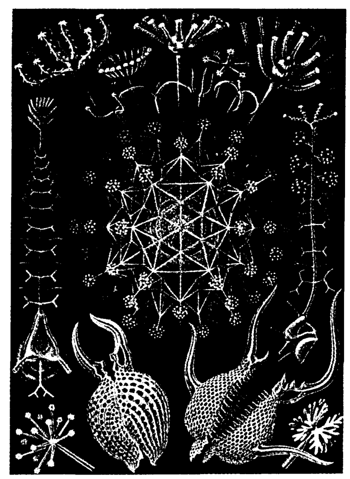
Perhaps the most sweeping statement of Platonic Oneness at mid-century – embracing industrialized structures as well as natural ones – was provided by R. Buckminster Fuller when he wrote that the 'subvisible microscopic animal structures called *radiolaria* are developed by the same mathematical and structural laws as those governing the man-designed geodesic and other non-man-designed spheroidal structures in nature'.[18] This similarity of underlying laws gave the radiolarians, like the geodesic domes that Fuller designed, the character of an exemplar for fundamental structures, which, he explained, were not in fact things but rather 'patterns of inherently regenerative constellar association of energy events'.[19] As if to substantiate Fuller's point, Paul Weidlinger illustrated his own account of the isomorphism in organic and inorganic materials as well as microscopic and macroscopic events, by comparing Haeckel's drawing of a radiolarian with magnified photographs of soap bubbles, the stellate cells of a reed and one of Fuller's geodesic domes, replete with tiny spikes that reinforce its resemblance to the radiolarian.[20]

18. R. Buckminster Fuller. 'Conceptuality of Fundamental Structures.' In Gyorgy Kepes, ed. *Structure in Art and in Science* (New York: George Braziller, 1965): 66–88. Quotation is on p. 80.

19. Ibid: 66.

20. Paul Weidlinger. 'Form in Engineering.' In Gyorgy Kepes, ed. *The New Landscape in Art and Science* (Chicago: Paul Theobald, 1956): 360–65.

Yet Thompson's lengthy effort to account for the diversity of the tiny creatures ultimately ran aground because of the impossible mathematics of Haeckel's theory of bio-crystallization. Not only did Thompson find it necessary to acknowledge and examine less perfectly configured specimens, such as the *Reticulum plasmatique* depicted by Carnoy, but in comparing them with Haeckel's *Aulonia* – 'looking like the finest imaginable Chinese ivory ball' – he invoked Euler to explain that '*No system of hexagons can enclose space*; whether the hexagons be equal or unequal, regular or irregular, it is still under all circumstances mathematically impossible ... the array of hexagons may be extended as far as you please, and over a surface either plane or curved, but *it never closes in*.'[21] Thompson pointed out that Haeckel himself must have been aware of the problem for, in his brief description of the *Aulonia hexagona*, he noted that a few square or pentagonal facets appeared among the hexagons. Thompson concluded from this that, while Haeckel tried hard to discover and reveal the symmetry of crystallization in radiolarians and other organisms, his effort 'resolves itself into remote analogies from which no conclusions can be drawn'. In the case of the radiolarians, 'Nature keeps some of her secrets longer than others.'[22]



Ernst Haeckel. Aulographis. Plate 61. *Kunstformen der Natur* (1904).

During the 1960s, armed with evidence from more powerful microscopes that the surface meshworks of radiolarians were in fact irregular, Phillip Ritterbush underscored the problem of regularity and biaxial symmetry when he suggested that Haeckel had altered his drawings of the radiolarians 'for them to conform more precisely to his belief in the geometric character of organisms'.[23] Ritterbush pointed

21. Thompson: 708.

22. Thompson: 732.

23. Phillip Ritterbush. *The Art of Organic Forms* (Washington: Smithsonian Institution Press, 1968): 8. See also Donna Jeanne Haraway. *Crystals, Fabrics, and Fields: Metaphors of Organicism in Twentieth-Century Developmental Biology* (New Haven and London: Yale University Press, 1976): 11.

out that Haeckel's appreciation of the regularities and symmetries of the skeletons of living organisms – and by extension, Fuller's conception of geodesic domes as manifesting patterns of constellar associations – relied on a permutation of the analogy with the crystal, which had been employed in biology since the seventeenth century. Nehemiah Grew (1628–1712), for instance, was an early plant anatomist who regarded regularities in natural forms as evidence that the processes of growth consisted of the repetition of simple steps, in which forms might be successfully analyzed.

Assuming that the modular regularity of the radiolarians demonstrated the existence of a universal transcendental order, Fuller reiterated it in the combinatorial logic of irreducible struts and universal joints that comprised his geodesic domes. In contrast, the botanist and popular science writer Raoul H. Francé had already in the 1920s interpreted the radiolarians within a cosmology of composite assemblages that understood all of creation to be constructed not of one Ur-element but of seven. In his *Die Pflanze als Erfinder* [The Plant as Inventor] (1920), Francé argued that the crystal, sphere, plane, rod, ribbon, screw and cone were the seven fundamental technical forms employed 'in various combinations by all world-processes, including architecture, machine elements, crystallography, chemistry, geography, astronomy, and art – every technique in the world'. Comparing what he called the 'biotechnics' of maple keys and tiny flagellates moving through rotation with ships' propellers underscored the isomorphism between human and natural works, inspiring the Russian artist–architect El Lissitzky to denounce the fixation with machines in the early 1920s in favour of constructing 'limbs of nature'.[24] Francé was read enthusiastically in the mid-1920s by artists and architects whom we associate with 'international constructivism' – not only El Lissitzky, but also Raoul Hausmann, László Moholy-Nagy, Hannes Meyer, Siegfried Ebeling and Ludwig Mies van der Rohe. So extensive was this reception of biotechnics or 'cosmobiotechnics', as Hausmann put it, that we may well refer to this orientation within constructivism as 'bioconstructivist'. Looking back, we may also recognize Berlage as providing an earlier iteration of bioconstructivist theory.

24. El Lissitzky and Kurt Schwitters, eds. 'Nasci,' *Merz* 8/9 (April/July 1924). See translation of text in Sophie Lissitzky-Küppers, *El Lissitzky: Life, Letters, Works* (London: Thames & Hudson, 1992): 351.

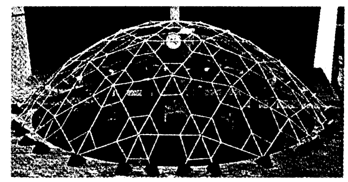
Lissitzky paraphrased Francé in his 'Nasci' issue of *Merz* in 1924, which he co-edited with Kurt Schwitters. It was there that Lissitzky gave a constructivist – and now scientific – twist to the idea of becoming that had saturated the artistic culture of Berlin after the Second World War, associated with both expressionism and dada. The word *nasci* is Latin for 'becoming' and approximates the German *Gestaltung*, which was used in technical discourse as well as aesthetics and biology and referred simultaneously to form and the process of formation. It implied a self-generating process of form-creation through which inner purposes or designs became visible in outer shapes. Having reiterated Francé's theory of biotechnics in their introduction to the journal, Lissitzky and Schwitters then provided a portfolio of modern artworks that can be interpreted only demonstrations of the theory. What is remarkable in this collection is the diversity produced with the seven technical forms. Beginning with Kasmir Malevich's Black Square, the folio then features one of Lissitzky's own Prouns; additional paintings by Piet Mondrian and Fernand Léger; collages by Schwitters, Hans Arp and Georges Braque; sculpture by Alexander Archipenko; photograms by Man Ray; and architecture by Vladimir Tatlin, J. J. P. Oud and Ludwig Mies van der Rohe, and several phenomena from nature. The sequence concludes with an unidentified microscopic image punctuated by a question-mark, suggesting something of the formlessness from which all form emerges or, perhaps, to which biotechnics might lead.

By the 1960s, scientists sought to come to terms with the limitations of the crystal metaphor for living phenomena. While Kathlene Lonsdale, for instance, attempted to shore up the transcendental authority of the crystalline by defining it more broadly as arrangements of atoms in repeating patterns,[25] the animal geneticist Conrad Waddington turned to other concepts to account for irregularities. Waddington used the radiolarians to discuss not the similarities between organic forms and technological objects but the difference between them, characterizing man-made objects as reductive, simplistic and mono-functional in relation to the complex, varied and multi-purpose nature of living organisms. For him, organic form 'is produced by the interaction of numerous forces which are balanced against one another in a near-equilibrium that has the character not of a precisely definable pattern but rather of a slightly fluid one, a rhythm.'[26] Invoking Alfred North Whitehead's conception of rhythm to address the irregularities that Thompson had already struggled with, Waddington wrote:

25. Kathlene Lonsdale. 'Art in Crystallography.' In Gyorgy Kepes, ed. *The New Landscape in Art and Science* (Chicago: Paul Theobald, 1956): 358.

26. C. H. Waddington. 'The Character of Biological Form.' In Lancelot Law Whyte, ed. *Aspects of Form* (London: Lund Humphries, 1951, 1968, 2nd edn): 43–52.

> It is instructive to compare the character of the variations from the ideal form in an organic and in human creation. The shell of the minute unicellular organism *Aulonia hexagona* is one of those animal structures whose functions are simple enough for it to approximate to a simple mathematical figure, that of a sphere covered by almost regular hexagons (fig. p. 365). It will be seen that the hexagons are in practice not quite regular; they do not make up a rigidly definable pattern, but rather a rhythm, in the sense of Whitehead, who wrote: 'A rhythm involves a pattern, and to that extent is always self-identical. But no rhythm can be a mere pattern; for the rhythmic quality depends equally upon the differences involved in each exhibition of the pattern. The essence of rhythm is the fusion of sameness and novelty; so that the whole never loses the essential unity of the pattern, while the parts exhibit the contrast arising from the novelty of the detail. A mere recurrence kills rhythm as surely as does a mere confusion of detail.'[27]



Robert Le Ricolais, Trihex dome, 1967–68 (From Peter McCleary, exhibition catalogue: *Robert Le Ricolais: Visions and Paradoxes*, 1997).

27. Waddington: 26. Waddington's citation of Whitehead is from Alfred North Whitehead, *The Principles of Natural Knowledge* (Cambridge, 1925): 198.

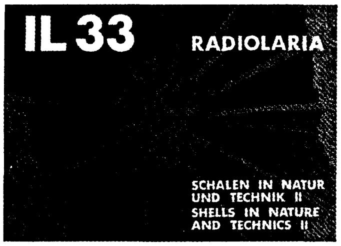
Like Waddington, the French–American structural engineer, Robert Le Ricolais – a pioneer of the space frame – insisted on distinguishing natural and man-made objects and on the limits of instrumental knowledge. While 'amazed' by the coherence and purity of design that the radiolarians represented, he also characterized it as 'frightening'. 'What man makes,' he wrote, 'is usually single-purposed, whereas nature is capable of fulfilling many requirements, not always clear to our mind.'[28] Where engineers had been speaking about space frames for only twenty-five or thirty years, the radiolarians were, he explained, three hundred million years old. 'Well, it's not by chance, and I'm glad that I saw the Radiolaria before I saw Mr. Fuller's dome.' Acknowledging that analogies with natural phenomena could help resolve some problems, he held that 'it's not so important to arrive at a particular solution as it is to get some general view of the whole damn thing, which leaves you guessing.'[29] Le Ricolais's use of material experiments was consistent with such scepticism, privileging specificity and concreteness over universal mathesis. Fascinated by the 'fantastic vastitude' of the radiolarians, neither Le Ricolais nor Frei Otto treated them as synecdochic for the entire universe.[30] They were merely one among many phenomena from which an engineer could learn.

28. Interview with Robert Le Ricolais. 'Things themselves are lying, and so are their images.' *VIA 2: Structures: Implicit and Explicit* (University of Pennsylvania, 1973): 91.

29. Ibid: 91.

30. Le Ricolais used the term 'vastitude' in describing the variety of radiolarians.

During this period, Frei Otto also took up the notion of self-generation and the analogy between biology and building, but eschewed the imitation of nature in



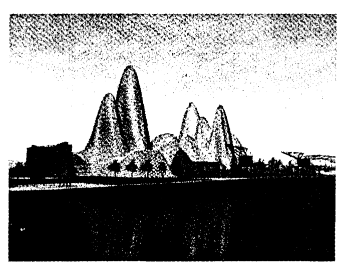
Frei Otto, Cover, *IL 33*, *Radiolaria: Shells in Nature and Technics II* (1990)

favour of working directly in materials to produce models that were at once natural *and* artificial. At the same time, he also eschewed their translation into a universalizing mathesis. Rather than focusing on form or formula, he took the idea of analogy in an entirely different direction, preferring to stage experiments in which materials find their own form. Where the theory of *Gestaltung* in the 1920s posited the unfolding of an essential germ from within, understanding external form as an expression of inner purpose, in the 1960s, autogenesis was redefined through cybernetics and systems theory, as a function of dynamic, open systems of organization and patterning. In this context, Otto's experiments in the form-finding potential of material process sidestep purist essentialism to open up a world in which unique and complex structures result immanently from material exigencies, without being subject to any transcendent authority, either internal or external. Otto's analogical models involve iterations at different scales and in different materials, but without positing an overarching totality, reductive universality or optimized homogeneity. Open to the air, rambling and polycentric, Otto's tensile structures operate demonstrably outside the terms of physiognomic and formal expression, leaving behind the problematics of inner–outer identity, closure and unity that had been integral to the modernist conception of the autonomous organism and of autopoiesis in human works.

It is telling that an entire issue of the *IL* journal of Otto's Institute for Lightweight Structures has been devoted to the radiolarians, whose composite of pneumatic and net structures intrigued Otto and his research group just as they did Le Ricolais. But unlike other admirers, Otto's group did not take these creatures as models for engineering, but rather sought to explain their self-generation with analogic models. Situated between natural phenomena and engineering, the isomorphic character of Otto's analogical models gives them not only instrumental value for new constructions but also explanatory power for natural phenomena.[31]

31. The 1990 issue of the journal of the Institute for Lightweight Structures, *IL 33*, was dedicated to explaining the self-generation process in some skeletons of radiolarians.

Spuybroek too is fascinated by the ways in which complex surfaces in nature result from the rigidification of flexible structures, a process so intricate as to elude precise theoretical or mathematical analysis. Like Otto, he uses a varied repertoire of analogical material models that are deceptively simple but remarkably effective for generating complex structures and tectonic surfaces. In his hands, the radiolarians are no longer emblems of universal order, their imperfections corrected into the perfect regularity of crystalline spheres. 'What is so interesting,' he writes, 'about radiolarians is that they are never spheres, though they tend towards the spherical. They are all composite spheres – tetrahedral, tubular, fan-shaped, etc.' Focusing on examples different from the perfect spheres singled out by Fuller, Spuybroek sees radiolarians not as homogeneous forms but as material technologies that produce hybrid tectonic surfaces – part pneumatic, part net structures – which are flexible in contour and shape. The rhythmic variability of these surfaces is achieved by changes in the size of openings and the thickness of the net fibres between them. With this shift from form to surface, Spuybroek leaves behind the modernist quest for the supposed self-same identity of the organism in favour of a surface that can be modulated to assume different shapes and sizes, but also architectural roles – from façades to roofs and from towers to vaults, halls and edges. While Spuybroek's bundle of interwoven towers for the World Trade Center in New York demonstrates the flexibility of radiolarian technology, the more recent project for the European Central Bank realizes its potential to operate simultaneously in a multitude of ways. More importantly still, Spuybroek's radiolarian tectonic surface is but one of an increasing repertoire of analogical models with



European Central Bank by NOX, see p. 292.

which he works. Like Berlage and Francé, his organon of techniques is heterogeneous and divergent rather than homogeneous and convergent. Unlike them, however, he is no longer concerned with the elemental in any way, nor with unifying underlying laws, be they mathematical or biological or both. Although he employs the radiolarian technology to achieve what he calls 'a strong expression of wholeness and pluriformity at the same time', his ECB is radically asymmetrical and irregular, polycentric and contingent. And while its pattern-structure implies repetition and extension, the buildings produced with it remain singular entities.

In taking over Otto's method, Spuybroek uses it as an abstract machine, understanding this term – and the broader pragmatics of which it is a part – through Gilles Deleuze and Felix Guattari.[32] In discussing regimes of signs in *A Thousand Plateaus: Capitalism and Schizophrenia* (1987), they isolate four components of pragmatics: the generative, the transformational, the abstract machine and the machinic. The generative, they say, 'shows how the various abstract regimes form concrete mixed semiotics, with what variants, how they combine, and which one is predominant.'[33] The transformational component, on the other hand, 'shows how these regimes of signs are translated into each other, especially when there is a creation of a new regime.'[34] But, they foreground the abstract machine, with its diagrammatic mode of operation, since it deterritorializes already established semiotic formations or assemblages, is 'independent of the forms and substances, expressions and contents it will distribute'[35] and plays a 'piloting role' in the construction of new realities. The machinic component, they conclude, shows 'how abstract machines are effectuated in concrete assemblages'.[36] While their understanding of the generative is recombinatory and thus avoids implications of beginning from nothing, rethinking the generative impulse of the historical avant-garde in terms of the abstract machine helps to discharge any residual transcendentalism that continues to attend narratives of self-generation, which appears so anachronistic when reiterated by architects today. It offers a stronger and sharper version of *Gestaltung*, detaching process now entirely from form and dynamic organization from *Gestalt*. Alternatively, we could say, with Zeynep Mennan, that it could lead to a *Gestalt*-switch, a new theory of *Gestalt* that would be adequate to complex, rhythmic and modulated forms of heterogeneity.[37] Rather than settling chaos into an order that presumes to transcend it, Spuybroek generates an architecture that is self-estranging and self-different, in which identity is hybrid, multiple and open-ended. If cosmological wholeness is an issue at all, it may now be assumed as given, no longer something lost and needing to be regained, as the romantics thought. Art need no longer dedicate itself to the production of wholeness, since it is inherently part of the cosmos, whatever limited understanding of it we humans may achieve. As Keller Easterling has argued in another context, we need no longer worry about the One, but only the many.[38] There is no need for closure, unity or system that assimilates everything into One. Extending the bioconstructivism of Berlage, Francé, Lissitzky and Otto, Spuybroek now engages only in endless experiments with materials, their processes and structural potentials. What he repeats are not entities or forms but techniques, developing a new *modus operandi* for acting constructively in the world. Rather than seeking to overcome the world or to assimilate difference to the sameness of underlying laws, he works to produce new iterations of reality, drawing on the potentials of matter for the ongoing production and enjoyment of heterogeneous events.

32. Gilles Deleuze and Félix Guattari, *A Thousand Plateaus: Capitalism and Schizophrenia*. Translation and foreword by Brian Massumi (Minneapolis: University of Minnesota Press, 1987).

33. Ibid: 139.

34. Ibid: 139.

35. Ibid: 141.

36. Ibid: 146.

37. Zeynep Mennan, 'Des formes non standard: un "Gestalt Switch".' In exhibition catalogue, *Architectures non standard* (Paris: Centre Pompidou, 2003): 34–41.

38. Keller Easterling presented this argument in a lecture at the University of Pennsylvania on November 19, 2003. See her forthcoming book, *Terra Incognita*.