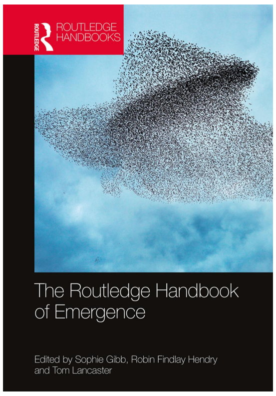

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EMERGENCE IN BIOLOGY
From organicism to systems biology

Emily Herring and Gregory Radick

Introduction

The idea that a causal system as a whole can have features that no one studying the component parts in isolation would have guessed predates the twentieth century. But the widespread use of the term "emergence" as a name for this idea does not. It derives from a 1923 book about evolution by the British scientist and philosopher Conwy Lloyd Morgan, *Emergent Evolution* (Morgan, 1923). Nowadays, Morgan's term leads two lives in biology. One is as the familiar label for an important but, from the perspective of conventional science, unchallenging class of phenomena. Richard Dawkins, the great publicist in our day for a disenchanted, matter-in-motion understanding of Darwinian nature, describes the human capacity to act against the interests of our selfish genes as an emergent property of brains that evolved in the service of those genes (Dawkins, 2017, pp. 3, 39–40). The term's other life – our main concern here – is more philosophically colourful and, for the likes of Dawkins, disreputable. Following Morgan's lead, emergence has been a perennially attractive option for biologists and others seeking a middle path between the extremes of what Morgan's generation called "mechanism" – the view that life is nothing but (and so fully reducible to) complex machinery – and "vitalism" – the view that life is something more than (and so not fully reducible to) complex machinery. Emergence in this anti-reductionist sense has overlapped untidily with a range of anti-reductionist stances and schools, from organicism in the first third of the twentieth century to systems biology in the first third of the twenty-first century. Even a brief history of emergence in biology will, of necessity, be a history of anti-reductionist tendencies in post-1900 biology more broadly.

Before and around organicism

Debating the autonomy of biology

The nature of biology's connection with the physical sciences and, relatedly, the status of biology as a science in its own right were common themes in the reflective writings of early twentieth-century biologists. One stimulus was the apparent success of mechanical explanation in the rapidly professionalizing biology of the later nineteenth century, notably in embryology, physiology, biochemistry, animal behaviour and – most famously – evolution. (It was in this period that Lamarckism, with its emphasis on animal activity as an evolutionary agent, acquired an anti-reductionist character that it retains to this day.) Another was the growing popularity, from 1900, of the mathematical Mendelian theory of heredity, widely touted as biology's atomic theory. In a 1911 address, the German-born American physiologist Jacques Loeb declared that "ultimately life, i.e., the sum of all life phenomena, can be unequivocally explained in physico-chemical terms" (Loeb, 1912, p. 3). A choice seemed to be forced. Either life was nothing more than physics and chemistry, in which case the science of biology was effectively an immature branch of the physical sciences, or life was not just physics and chemistry, in which case biology was a truly autonomous science, standing on its own feet. But what, metaphysically considered, did those feet stand upon? Did autonomy require the positing of irreducibly biological and even teleological forces, along the lines of the *entelechies* invoked by the embryologist Hans Driesch to explain development (Driesch, 1900)? If so, then, for Loeb and like-minded thinkers, the price of autonomy seemed to be vitalism, and so a turning away from anything recognisable as modern science since the reforms of Bacon and Descartes.

In Britain, several biologists sought to articulate a third way. They defended the idea that biology was undergoing – or needed to undergo – some sort of theoretical and methodological redefinition which would establish its autonomy by enabling biologists to explain the phenomena of life and mind on distinctively biological terms, the better to meet the overriding scientific goal of giving a correct account of nature and its workings (Thomson, 1911; Johnstone, 1914; Darbishire, 1917). These efforts often involved severe criticisms of Mendelian genetics and the neo-Darwinian theory of natural selection, viewed as the most prominent biological manifestations of reductive mechanism. After World War I, resistance to a fully physicalized biology grew stronger, thanks to developments outside as well as inside biology. Outside biology, mechanism and reductionism in some quarters became associated with the evils of war (Harrington, 1996), while the rise of the quantum theory within the physical sciences was seen as discrediting the old clockwork image of deterministic nature. Within biology, meanwhile, the search for alternatives drew inspiration from several different sources. We shall touch on three that took shape around the same time as organicism. One was Morgan's evolutionary biology of emergence. The other two arose in association with resurgent romantic holism and a new metaphysics of life-as-process. (The term "holism," it should be noted, is a product of the same period and conversation, coined by the South African statesman and philosopher Jan Smuts in a book on evolution; see Smuts, 1926.)

Resurgent romantic holism

A great deal of early twentieth-century organism-centred biology in Germany and Austria (Harrington, 1996), as well as in Germanophile British and American biology (Esposito, 2013), continued a tradition of romantic holism tracing back to Johann Wolfgang von Goethe's appropriation of the philosophy of Immanuel Kant. Goethe, inventor of morphology, was particularly impressed with Kant's definition of organisms as self-generating, self-organising wholes. For Kant, human understanding of organisms required them to be considered teleological entities, with the activities of the parts subservient to the needs of the whole. ("There will never be a Newton of a blade of grass" became Kant's great one-liner against mechanistic biology.) The enduring legacy from this post-1900 boom in Kantian-Goethean biology is the Scottish morphologist D'Arcy W. Thompson's *On Growth and Form*, first published in 1917. Although the book's emphasis on geometry and physics made Thompson a grassblade-Newton (or perhaps grassblade-Maxwell) hero to later generations of reductionists, Thompson saw himself as striking a blow for the view that, as he wrote, when it comes to organisms,

> the whole is not merely the sum of its parts. It is this, and much more than this. For it is . . . an organization of parts, of parts in their mutual arrangements, fitting one with another in what Aristotle calls "a single and indivisible principle of unity."
>
> *(Thompson, 1942, p. 1019, quoted in Esposito, 2013, p. 78)*

A new metaphysics of life-as-process

The French philosopher Henri Bergson's metaphysically rich interpretation of biological evolution, developed in *L'Evolution Créatrice* (Bergson, 1907), had enormous appeal across professional biology, from the neo-Darwinian end (Gayon, 2008) through to the neo-Lamarckian end (Herring, 2016). Bergson introduced what he called an "image" (Bergson, 1907, p. 258), the *élan vital*, to characterize the history of life as a dynamic, unitary, self-creating whole, consisting of successive divisions stemming from the same original impulse and pursuing a common progressive tendency. Bergson's philosophy was profoundly anti-mechanistic and anti-deterministic, centring on the idea that the evolution of life is, in its details, an inherently unpredictable (and therefore, for Bergson, non-teleological), internally driven movement of complexification, in the direction of the development of more and more sophisticated minds. The British philosopher Alfred North Whitehead acknowledged Bergson's influence on his own process philosophy (Whitehead, 1929, p. xii). Criticising mechanistic trends in science, Whitehead proposed that scientists should concentrate on "multi-perspectival networks of relationships," rather than on "the behaviour of aggregated atomic units" (Peterson, 2014, p. 286). His philosophy of the organism (Whitehead, 1920, 1925) went on, as we shall see, to inspire the British organicists of the 1930s.

Emergent evolution

Favourably disposed towards Bergson's and Whitehead's anti-mechanistic metaphysics (Blitz, 1992, p. 91), Conwy Lloyd Morgan came to similar views independently through reflections that began for him as a student of Thomas Huxley's. Contra Darwin, Huxley thought that nature occasionally makes leaps. Morgan turned that teaching into a rule of method for comparative psychology, "Morgan's canon," first promulgated in the 1890s, and commanding investigators not to attribute cognitively rich powers to the animal mind (i.e. powers of reason) when more humble powers (i.e. trial-and-error learning) will serve, on the view that reason-and-language-enabled human minds are different in kind from the minds of our evolutionary kin. The doctrine of emergence was Morgan's canon generalized to the whole of evolution, indeed the whole universe, understood as a system in which, level by level, spirit manifests in new and ever more complex forms, first of matter, then of life, then finally of mind (Radick, 2004; Morgan, 1923).[1] "The whole doctrine of emergence," wrote Morgan, "is a continued protest against mechanical interpretation, and the very antithesis to one that is mechanistic" (Morgan, 1923, pp. 6–7). Behind that protest lay not just Huxleyan biology but, among other sources, Herbert Spencer's evolutionary philosophy, which likewise emphasized progression towards complexity and distinguished three levels successively attained by universal evolution: the "inorganic," the "organic" and the "super-organic" (Blitz, 1992). For Morgan – and also for another of the era's philosophers of life and mind, the less well-remembered Leonard Hobhouse – appreciation of the qualitative novelty of the emerging levels went along with a need to recognize that methods of investigation appropriate for one level could not be transferred to a higher level (Radick, 2017).

Organicism

Early organicism

Energized by this ambient, multi-source biological anti-mechanism, the Scottish physiologist John Scott Haldane, in lectures published the same year as of *On Growth and Form*, proposed his own solution to the shortcomings of both mechanistic and vitalistic views. Pointing out that biological phenomena such as self-regulation arose from interactions between the different parts and levels of the organism, Haldane argued that organisms themselves need to be studied as complex wholes, irreducible to the physico-chemical elements composing them. He insisted that this view did not amount to a disguised form of vitalism and explicitly excluded explanations relying on immaterial internal forces. In a footnote, he suggested a name for this organism-focused doctrine: "organicism" (Haldane, 1917, p. 3).[2] Soon others would publish along similarly organicist lines, including the American biologist William Emerson Ritter, who laid out the principles for his own "organismal conception of life" in a two-volume work (Ritter, 1919); the Scottish biologist E.S. Russell, who defended "the validity and independence of biological laws over against the laws of physics and chemistry" (Russell, 1924, p. 41); and the English philosopher Joseph Henry Woodger, author of *Biological Principles* (Woodger, 1929), which went on to be a "cornerstone theoretical text of the 'third way'" (Peterson, 2016, p. 62). These organismic thinkers all shared a commitment to viewing the organism as a hierarchical complex whose properties at any given level of organization emerged from interactions among the parts at a lower level. By the 1930s, a younger generation of self-identified organicists was building upon the foundations put in place by the previous generation.

The Theoretical Biology Club

A prominent member of this younger generation was the English biochemist Joseph Needham, who had converted from reductionism to third-way thinking in the late 1920s through correspondence with Woodger. Along with the Edinburgh-based evolutionary embryologist Conrad Hal Waddington, Needham and Woodger attempted to launch an organicist research programme – an ambition recently given a boost by the experiments of the Berlin embryologist Hans Spemann, who had shown, with German embryologist Hilde Mangold, that certain areas of the embryo (what he called the "organizer centres") induced the organization of the adjacent areas (Spemann and Mangold, 1924). The challenge of understanding these organizer centres attracted the new British organicists, who saw in the problem a potentially tractable version of the larger problem of understanding the hierarchical self-organizing properties of life. In 1931, Needham and his wife, the biochemist Dorothy Needham, deciding to join the organizer "scientific gold rush," moved to Berlin, where they became Waddington's neighbours (Peterson, 2016, pp. 93, 103). By the end of the year, the Needhams and Waddington were back in Britain and eager to pursue their organismic research. The following spring, the first meeting of the Theoretical Biology Club took place in Woodger's summer cabin. In addition to the Needhams, Woodger and Waddington, the crystallographer J.D. Bernal and the mathematician Dorothy Wrinch attended.

The mix of disciplines reflected and expressed a shared commitment to trying to understand organisms holistically. Other sources of unity included a common left-wing politics and, notwithstanding the professional success of many, a sense of outsider, even outlaw, status. They were unashamedly intellectual, drawing not just on Whitehead's process philosophy but also the logical positivism of the Vienna Circle, along with the latest work in symbolic logic and mathematics. In their meetings, held once or twice a year over a period of six years, they discussed problems such as Spemann's organizer, geometrical patterning in biology, philosophy of science and language, as well as socialism (for a more detailed account see Abir-Am, 1987). Over the course of the club's existence, Needham and Woodger published their most important works in organismic biology (Needham, 1932, 1936; Woodger, 1930a, 1930b, 1931), while the Needhams and Waddington were pursuing their organizer research, making Cambridge a centre of research in experimental embryology until the late 1930s (Peterson, 2014, p. 291).

From 1934, Joseph Needham began negotiations with the New York–based Rockefeller Foundation to obtain funding for a laboratory in Cambridge, in the hope of institutionalizing the club's research programme. A first proposal, seeking funds for seven interlinked research facilities devoted to embryology in all its aspects from the experimental to the psychological, was deemed too ambitious, with the multidisciplinary aspect of the project viewed as a handicap (Peterson, 2016, p. 118). Needham subsequently scaled down his requests, but these less ambitious proposals too were rejected. Although some historians suggest that this failure can be put down to the increasing success of mechanistic approaches in biology (Bowler, 2001, pp. 174–175) – and indeed, it was at just this time that the Rockefeller Foundation began promoting the new science of molecular biology – the foundation's growing awareness of how little support the club had in Cambridge itself was at least as important. The club's socialist-communist ties did nothing to help its cause (Peterson, 2016, p. 119).

Organisms as systems: Ludwig von Bertalanffy

Britain was not the only country in which third-way solutions were being proposed in this period. In Austria, the embryologist Ludwig von Bertalanffy developed his own "organismic" theory of life. Often cited as a founding figure for systems theory and systems biology, Bertalanffy always acknowledged his debt to another Austrian biologist, Paul A. Weiss, who used the notion of organisms as systems to criticize Loeb's reductionist approach to animal behaviour (Weiss, 1925). Learning about British organicism, Bertalanffy in the late 1920s started corresponding and collaborating with Woodger. Their discussions led to a translated and revised edition of Bertalanffy's 1928 manifesto for a "critical theory of morphogenesis" (Bertalanffy, 1928). Published in 1933 under the title *Modern Theories of Development, An Introduction to Theoretical Biology*, it argued that biology was in need of a "theoretical clarification" (Bertalanffy, 1933, p. 4) that would distinguish it from a simple collection of empirical facts and give it the status of a full-grown theoretical science with its own laws. To this end, Bertalanffy propounded what he called "an *organismic* or *system theory* of the organism," which subscribed neither to "machine theory" nor to a vitalistic "mystical entelechy" (Bertalanffy, 1933, pp. 177–178). Eschewing an analytico-summative manner, by which the organism was analysed into its separate parts (cells or characters, for instance) and studied as nothing more than the sum of these parts, Bertalanffy proposed considering the organism as a system, that is, as a constellation of elements mutually interacting in order to maintain a state of dynamic equilibrium. His "system theory" of the organism aimed to provide the framework to study "the forces immanent in the living system itself" (Bertalanffy, 1933, pp. 177–178) – that is, the interactions between the parts of the system which brought about the hierarchical order characteristic of the organism.

The politics of organicism

In the German-speaking world, the political appropriations of organismic and holistic theories served a radically different ideological agenda than that of the socialist organicism of the Theoretical Biology Club. The British organicists of the left used analogies between organism and society in order to argue for a socialist ideal of cooperation in the interest of the parts and the whole, and often viewed the third-way synthesis between mechanism and vitalism as a form of Marxist dialectic. In Germany and Austria during the same period, by contrast, holistic ideals were instead being used to serve the fascist and racist agenda of National Socialism, with mechanistic science increasingly disparaged as the work of Jews, and comparisons between state and organism served the purpose of asserting the superiority of the whole by negating the power of its individual parts (Harrington, 1996, p. 175). Whether it was out of conviction, opportunism or (most likely) both, Bertalanffy joined those thinkers who explicitly linked their organismic biology to totalitarianism. While he apparently voiced disapproval of Nazi policies at first, Bertalanffy ended up joining the Nazi Party in 1938, after the annexation of Austria by Hitler. Academic promotion followed in short order (Drack et al., 2007, pp. 361–362; cf. Burkhardt, 2005, ch. 5, for the comparable case of Konrad Lorenz, whose science of ethology was likewise pitched between mechanism and vitalism).

After the Second World War, the term "organicism" became increasingly associated with discredited ideology rather than creditable science. One of the unfortunate effects was to obscure the diversity and even real achievements of the emergentist, holistic, organicist biology of the interwar years. As we have seen, although it did not last long, the left-leaning Theoretical Biology Club went some way toward showing what such a biology would look like in practice. But if the term "organicism" did not survive, the programme did, as well as key proponents such as Bertalanffy. Before he could be prosecuted during the denazification process after World War II he emigrated to Britain and then Canada, where he began promoting what he now labelled "general systems theory." This time his ideas were met with greater institutional enthusiasm, as systems thinking and mathematized models more generally came to be seen increasingly as promising ripostes to the challenges posed by new forms of post-war reductionism.

Developments after the Second World War

The triumph of the new reductionism

In the 1940s, discoveries in biochemistry later regarded as foundational for molecular biology, such as Beadle and Tatum's one-gene-one-enzyme hypothesis (Beadle and Tatum, 1941), strengthened confidence in reductionist quarters that biology could be unified from the bottom up, that is, from the simple to the complex, from molecule to organism. The post-war period generally saw reductionist approaches in biology go from strength to strength. One source of this recovered momentum was the intellectual migration of accomplished physicists into biology, among them George Gamow and Erwin Schrödinger (Schrödinger, 1944), thanks in part to the attractiveness of the exciting new problems and in part to the unattractive weaponization of physics during the war (Morange, 1994, pp. 92–93). Major achievements flowed swiftly, most famously the discovery of the double-helical structure of DNA, the chemical basis of the gene, by James Watson and Francis Crick (another ex-physicist) in 1953; Crick's formulation of the "central dogma of molecular biology" in 1957;[3] and the relating of DNA's structure to its function via the working out, by the mid-1960s, of the genetic code, linking nucleotide sequences in genes to amino acid sequences in proteins.

Watson and Crick famously claimed to have discovered not just the structure of a molecule but "the secret of life." That bold statement has since been understood as a calculated coup against their opponents in the context of a cultural war, with the materialist and reductionist Watson and Crick hoping this would be the final blow against their holist and spiritualist adversaries (Bud, 2013). And indeed, the publicizing in the 1960s of DNA-centric views by science popularizers such as Isaac Asimov (Asimov, 1960) helped to spread the idea that the organism is nothing more than the sum of its molecular components or the sum of the effects of its discrete genes. Even so, aspirations for a different model for biological thinking, one that would endeavour to come up with new ways to apprehend the complexity of life, not only survived but thrived across the same period and beyond.

Taking complexity seriously

For some, a science that could crack the problem of organized complexity in biology – a problem that molecular biology seemed to them utterly incapable of addressing, let alone solving – was the key not just to understanding life but to understanding more or less everything. They found an influential spokesman in Bertalanffy, whose project for a general systems theory started reaching wider audiences in the 1950s and 1960s. In calling it a "general" theory, he meant it. In Bertalanffy's words, his general system theory was "a general science of 'wholeness' which up till now was considered a vague, hazy and semi-metaphysical concept. In elaborate form it would be a logico-mathematical discipline, in itself formal but applicable to the various empirical sciences" (von Bertalanffy, 1969, p. 37). Those sciences included particle physics, psychology, the social sciences and potentially even disciplines such as history. Such radical inclusiveness did not at all suggest that different levels of the hierarchic structure of the universe could all be collapsed into one another. On the contrary, the study of organization would likely bring the recognition of new types of laws.

> To arrive at such organizational laws . . . we need on the one hand, empirical investigation and definition in each case and at each particular level. On the other hand we need a general conceptual framework which transcends that of traditional science.
>
> *(von Bertalanffy, 1969, p. 59)*

Bertalanffy was far from alone. In the 1940s and 1950s, other influential attempts were made to construct mathematical models and laws which would apply to different types of systems and were thought to have the potential to unify science. These included the Belgian chemist (and future Nobelist) Ilya Prigogine's study of non-equilibrium thermodynamics (Prigogine, 1947); the American mathematician Norbert Wiener's cybernetics (Wiener, 1948), which studied the transfer of information in self-regulating systems; and the beginnings of what would develop, in later decades, into catastrophe theory, chaos theory and complexity theory. A reviewer for the first volume of the *Yearbook of the Society for the Advancement of General Systems Theory* characterized ambitions along these lines as the search for "potentially universal methods" (Whyte, 1956, p. 171). As the title of that volume suggests, the Bertalanffyan end of the search was especially successful institutionally. In 1954, he founded the Society for the Advancement of General Systems Theory[4] alongside the neurophysiologist and behavioural scientist Ralph Gerard and the economist Kenneth Boulding. Among the aims of the society in their initial programme were to "investigate the isomorphy of concepts, laws and models in various fields, and to help in useful transfers from one field to another," as well as to "promote the unity of science through improving communication among specialists."

Anti-reductionist evolution: a return for emergence

Another flank in the post-war rise of reductionist biology was the Neo-Darwinian theoretical enterprise that Julian Huxley named "The Modern Synthesis" (Huxley, 1942): the union of Mendelian genetics and Darwinian natural selection. Nevertheless, emergentism soon found its way back into evolutionary thinking, as a way of blunting the edge of the idea that evolution was nothing more than the outcome of changes in the frequencies of randomly mutating genes. In France, Pierre Teilhard de Chardin, a controversial but very influential French Jesuit palaeontologist, gave emergent evolution a theological spin. In his posthumously published *Phenomenon of Man* (Teilhard de Chardin, 1955), he depicted evolution as a universal movement of complexification and the universe as a hierarchical system composed of emergent levels: "Pre-Life," "Life" (the biosphere) and "Human Consciousness" (the "noosphere" – a term borrowed from the Ukrainian chemist Vladimir Verdnasky). The ultimate development of evolution would be "the Omega Point," a point of divine convergence of all spheres of consciousness. Despite being accused of producing nothing more than pseudo-scientific mystical nonsense by two Nobel Prize laureates, Peter Medawar and Jacques Monod (Medawar, 1961; Monod, 1970), Teilhard de Chardin had a strong following not only among French Neo-Lamarckians such as Albert Vandel and Pierre-Paul Grassé but also among the architects of the Modern Synthesis, notably Julian Huxley and Theodosius Dobzhansky, who, in the later stages of their careers developed emergentist visions of evolution, inspired by his ideas.

The specifically Lloyd Morgan version of "emergence" talk and thinking re-entered anti-reductionist discussions in the 1950s and 1960s via another one of Teilhard de Chardin's readers, the British-Hungarian chemist and polymath Michael Polanyi, author of the philosophy-of-science classic *Personal Knowledge* (1958). According to Polanyi, the Neo-Darwinian theory of evolution carried a "fundamental vagueness" (Polanyi, 1962, p. 383), arising from its reductionist definition of life in terms of physics and chemistry. Polanyi posited a teleological and irreducible "ordering principle" or an "orderly innovating principle" to explain evolution as the emergence of radical and irreducible novelties. Thanks to Polanyi's advocacy, in that book and elsewhere (see, e.g., Polanyi, 1968), the doctrine of emergence once again became a lively resource for anti-reductionist biologist thinkers, as one can see in the writings in this period of the Cambridge-based Quaker ethologist William Thorpe (Radick, 2017).

Systems biology

In 1966, the Serbian scientist Mihajlo D. Mesarovic, at the time head of the Systems Engineering Group at Case Western Reserve University in Cleveland, organized a symposium themed around systems thinking. This symposium was the third on the subject of systems, but the first focussing specifically on systems theory in relation to biology. In the introduction to the proceedings of the symposium (Mesarovic, 1968), Mesarovic put systems at the centre of biological inquiry. "The fundamental question for the community of biologists is whether an explanation on the systems theoretic basis is acceptable as a true scientific explanation in the biological inquiry" (p. 76), he wrote, adding: "If the answer to the question of the acceptance of systems-theoretic explanations in biology is in the affirmative (as I contend) then . . . [we will have] a field of systems biology with its own identity and in its own right" (p. 77). In 1968, a reviewer of the proceedings represented systems biology as a new form of holistic reaction against the reductionist excesses of molecular biology, predicting that system-theoretic concepts were destined to play an important role in the future of biology and recommending his readers familiarize themselves with these concepts (Rosen, 1968, with Mesarovic quoted on p. 34).

That same year, in the Austrian village of Alpbach, the British-Hungarian man of letters and Cold Warrior Arthur Koestler gathered scientists from various disciplines for a symposium to reflect on ways of going "Beyond Reductionism," aiming to re-examine what he called the "totalitarian claims of the Neo-Darwinian orthodoxy" and its molecular-biological outrider (Koestler and Smythies, 1969, p. 1). Among the invitees were several figures already mentioned, including Waddington, Thorpe and the systems theorists Bertalanffy and Weiss. Both of the latter represented themselves as opposed to the reductionism of molecular approaches, with Weiss speaking in favour of a more interdisciplinary biological science (Koestler and Smythies, 1969,

p. 3), seeking a more synthetic (i.e. less atomistic and analytic) understanding of organisms. Notwithstanding the like-mindedness of the symposiasts in so many ways, however, no consensus was reached of what it meant to be an anti-reductionist biologist (Stark, 2016).

Over the course of the next decades, new ways of modelling biological systems emerged, from the biochemical systems theory and metabolic control theory that developed in the 1960s and 1970s through to the first *in silico* models of cells and viruses. At the same time, new prospects for advancing systems-oriented biology arose from the increasing powers of biologists, both to gather vast amounts of data – thanks especially to the automated genome-sequencing techniques developed in the 1990s and by the early 2000s – and to process that data using increasingly powerful computers. Key aspects of systems thinking have since been popularized in science books aimed at the general public (see, e.g., Noble, 2006). But there have also been major disciplinary developments within professional biology. "Systems biology" is increasingly a fully institutionalized, specialized branch of science, with its own journals, societies, textbooks and university departments with teaching programmes. On the website of the Department of Systems Biology at Harvard Medical School, we meet the following message of welcome:

> Systems biology is the study of systems of biological components, which may be molecules, cells, organisms or entire species. Living systems are dynamic and complex, and their behavior may be hard to predict from the properties of individual parts. To study them, we use quantitative measurements of the behavior of groups of interacting components, systematic measurement technologies such as genomics, bioinformatics and proteomics, and mathematical and computational models to describe and predict dynamical behavior. Systems problems are emerging as central to all areas of biology and medicine.

A lot of the past century's anti-reductionist buzzwords are present, and indeed systems biologists mostly, if not exclusively, identify as anti-reductionists (Calvert and Fujimura, 2009). Is anti-reductionist biology so configured headed for an institutionally secure future? The history we have reviewed here suggests caution. As we have seen, "organicism" was a name devised and adopted by biologists who viewed their discipline as in crisis because torn between two impossible-to-reconcile extremes, vitalism and mechanism. Likewise, for some at least, "systems biology" has come to designate less a new solution to the old problems than a new label for them. It is "the name of the crisis," as one systems biologist remarked; "it's the name of the fright that every one's gone into about having all the pieces and still not knowing how biology works" (Calvert and Fujimura, 2009, p. 48).

Notes

1 In his 1922 Gifford lectures "Emergent Evolution," Morgan explicitly framed his conception of emergence in terms of higher and lower levels (Morgan, 1923).
2 Haldane added that this term was not original to him but had previously been used to describe the theories of Xavier Bichat, Karl Ernst von Baer and Claude Bernard.
3 The central dogma held that the transfer of information was strictly unidirectional from DNA to RNA to protein.
4 The society is now called the International Society for the Systems Sciences.

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