2023

Process Epistemologies For The Careful Interplay Of Art And Biology: An Afterword

S. R. Gilbert

Scott F. Gilbert
Swarthmore College, sgilber1@swarthmore.edu

Recommended Citation

S. R. Gilbert and Scott F. Gilbert. (2023). "Process Epistemologies For The Careful Interplay Of Art And Biology: An Afterword". *Drawing Processes Of Life: Molecules, Cells, Organisms.* 295-320. DOI: 10.2307/jj.6947019.17
https://works.swarthmore.edu/fac-biology/641

Process Epistemologies for the Careful Interplay of Art and Biology: An Afterword

Sarah R. Gilbert and Scott F. Gilbert

A book – like an organism, like an artwork – is always more than the sum of its parts. As a gathering of practices dispersed across the too often-siloed fields of art, science and philosophy, this book offers a rare opportunity to un-discipline urgent questions around changing life. This is not to say that disciplinary assumptions and methodologies are absent. Quite to the contrary, the included papers explore a wide range of what Haraway (1988) calls 'situated knowledges': explicitly partial perspectives that allow us to become accountable to each other for how we learn. Notably, each practitioner in this volume brings not only their own bundle of situated expertise and skills but also a commitment to loosening or even undoing, some of the disciplinary strictures and other habits of thought that often constrain thinking across divergent practices. Put simply, the participants of this project came to play, eager to learn from the unexpected affiliations and generative frictions of this encounter.

When Gemma and John invited us to reflect on, amplify and interact with these thought-provoking contributions, we were happy to join the party. The time was certainly ripe for such a symposium, as ideas of the process have created new priorities in the field of biology and its visual representations. The result is a book that asks us to follow various problems and practices as they move betwixt the unstable territories of what we casually call 'Science', 'Art' and 'Philosophy' – hardly settled and uniform fields, but rather shifting sets of heterogeneous practices tending to cluster around different modes of thought.

Different modes of thought are important because they allow different kinds of problems and questions to become intelligible. It has been said many times, but it bears repeating (from the rooftops!): we are not interested in one true epistemology to rule over all others. We must instead work to aid in the survival and proliferation of specifically situated knowledge practices. Thinking about life's processes alongside practitioners in this book and beyond, we aim to draw out disparate threads of particular 'stickiness', resisting the tendency to collapse difference into an agreement or, in Haraway's terms, to equate thinking with the 'dispelling of trouble' (Haraway 2016). Far from undermining Art/Science collaborations, we hope that these nagging threads, if pulled hard enough or in relevant directions, might do some useful work in helping to unravel the still persistent myth of C. P. Snow's 'two cultures' (Snow 1959) and the tired battles still being fought over each culture's claim to epistemological superiority. Supporting instead what Isabelle Stengers (2017) calls 'an ecology of practices', we write here collaboratively, as practitioners of different crafts (in the most general terms of sculpture and biology, respectively) with 'an active sense of the positive partiality of our practice[s]'.

Changing biology by changing drawing/changing drawing by changing biology

In his analysis of Cézanne's drawings, art critic Peter Schjeldahl (2021) has written about 'the timeless purpose – and the impossibility – of pictorial art: to reduce three dimensions to two'. How much greater, then, is the impossibility of reducing four biological dimensions (the fourth being time) to a two-dimensional space? John Dupré brings to the discussion the concept of process biology, both in its ontology and epistemology, emphasizing that biological entities can be seen as processes as well as objects. Until recently, biology has centred around organisms, organ systems, their cells and their genes. So it is not surprising that scientific drawing has focused on the attempt to represent entities, not processes. Such drawing skills used to be part of the biological curriculum, and biologists had been instructed that if you haven't drawn it, you haven't seen it (Root-Bernstein and Root-Bernstein 1999; Gilbert and Faber 1996).

In biological illustration, there are, perhaps, four major perspectives, four modes of relationships into which living beings are placed: the mode of a predator, the mode of a connoisseur, the mode of an abstractionist and the mode of a romantic. Each is needed, and each is incomplete. The 'predatory mode' is highly developed in the naturalist, and it is the ability to spot a salamander camouflaged in the soil or a butterfly on a vine. The 'connoisseur's mode' is the ability that can look at a thrip and identify its family from the shape of its tenth abdominal segment. This mode of viewing life is often highly developed in professional biologists.

Both predatory and connoisseurial perspectives are important in biology. Darwin had the predatory eye of a naturalist, honed by years of collecting beetles in the fens of England. He also had a connoisseur's eye, but only for barnacles. He didn't recognize, for instance, that the birds he had collected in the Galapagos were all finches. The bird expert, the ornithologist/artist John Gould, had to tell him that. The realistic representations of turtles in art, textbooks and monographs provide another example of both types of eyes. David Carroll, for instance, has a trained naturalist's eye that can recognize a turtle on the banks of a sandbar laying her eggs in the late evening. For Carroll, who consciously calls his contributions 'natural history', context is critical (Carroll 1996), and his turtles are represented in their respective environments. His turtles are always doing something.

For Louis Agassiz, the critically important Harvard biologist of the late nineteenth century, turtles were drawn only after the turtle was removed from its environment and brought into his laboratory. Agassiz's book on turtle embryology is a classic, and one of the most beautifully illustrated biological monographs ever published (Agassiz 1857). However, it is a museum offering. The stages of turtle development are not in a linear sequence. Adult and embryonic stages are placed alongside one another in frames, and one can imagine oneself looking down at a museum drawer, where the specimens are laid out for your viewing. Agassiz was the prime museum enthusiast in America (Winsor 1979; Lurie 1988), and the full name for the MCZ had long been 'The Louis Agassiz Museum of Comparative Zoology'.[1] The Museum opened in 1859, two years after the turtle volume. Indeed, the turtle volume can be considered as an extension of Agassiz's new museum.

Agassiz helped change biology by changing the way turtles were represented. Agassiz was branding himself as a 'scientist', and as Laura Dassow Walls has shown, he and other scientists were becoming 'modern' through their separation from nature and their ability to stand above it (Walls 1997). He denigrated 'natural history', relegating field biology to a second-rate status suitable for amateurs (Tauber 2001). Agassiz was himself an artist who taught his students to draw specimens, but they were dead specimens in a classroom dish or a laboratory pan, not in a pond or stream. Walls notes that Agassiz praised natural history in his act of 'purifying' it.

> But while Humboldt enacted his method in the chaotic conditions of the field, Agassiz enacts the Humboldtian method in the vacuum of the laboratory, thereby gaining precision and control. Agassiz both honored his mentor's name and warned against imitating him.
>
> (Walls 1997: 24)

The 'epistemic virtue' (Daston and Galison 2010) of animals being represented in context is being replaced by one of precise isolated objectivity. Agassiz trained his students for connoisseurship, and many were awarded choice positions in American universities.

In other words, the manner of drawing – the detachment of the organism from its environment – helped create a manner of science. And that type of science promoted that manner of drawing. By drawing specimens out of their context and individuated, Agassiz had used drawing to reframe organisms, taking them out of natural history and into a 'modern' science. This is an important lesson for those seeking a similar revolution in biology today, promoted in part, by its art.

We also see this symbiosis of science and drawing in the study of insect metamorphosis. Janina Wellman, in this current volume, shows that while K. E. von Baer and H. Rathke helped free the study of vertebrate development from the paradigm of preformationism, Johann M. D. Herold was showing epigenesis (and not preformationism) in insects. While Pander and von Baer observed germ layers and guts to establish that organisms formed their organs anew each generation, Herold looked at the generative organs of butterflies and produced panels of drawings to show their gradual developmental changes. This way of showing process has become normative in embryology texts. Here, too, a change in drawing style accompanied the change in biological paradigm.

But to draw a biology of processes, one needs to have the 'abstractionist' mode to imagine the process as an entity, itself. The naturalist painter Maria Sybilla Merian may have drawn the first abstractionist renderings of life (Merian 1705; Todd 2007; Nutting 2011). Here, again, insect metamorphosis was used as an exemplary process. Though her lithographs included realistic depictions of nature, she arranged the drawings of eggs, larvae, pupae and adults to show an abstract process, the insect life cycle, something never before depicted. The egg (and the plant upon which it was laid), the larva (eating that plant), the pupa and the adult butterfly were all on the same page, creating something new – the life cycle. Taking science to a new level, emphasizing life cycles and interspecies relationships, she also changed the art. Botanical images of her period had favoured grid-like treatments, emphasizing similarities (Jardine et al. 1996: 101; Reitsma 2008: 209). Merian's portrayal of nature reflected the vibrant and varied environments of the South American tropics.

The abstractionist mode was first recognized by diachronic biologist Conrad Hal Waddington (1968), who felt that in the twentieth century, both art and science had tried to get 'beyond appearances'. This led to movements towards abstractions in both art and biology (where genetics provided a look 'beyond' the phenotype). The abstractive view can be seen in the Watson and Crick models of the double helix and in Jane Richardson's drawings of protein structure. These semi-diagrammatic representations remove the physicality from the molecules and just show the framework that gives the molecule its functions.

John Dupré has emphasized that life is sustained predominantly by three processes: metabolism, the life cycle and symbiosis. Metabolism is nothing less than the ability of an organism to retain its identity by changing its parts (Jonas 1966). It is one of the major ways of characterizing life. When it comes to the life cycle, one of the most influential process biologists has been John Tyler Bonner. Whereas even process philosophers such as John Dupré will say that 'organisms have life cycles'. Bonner (Bonner 1965; Gilbert 2019) postulated that organisms *are* life cycles. Indeed, seeing things this way – the body as part of the life cycle process – allows one to see (as Dupré has suggested in his talk) that Boris Johnson is both egg and prime minister. Symbiosis is shown as the third process of life, and all animals share the property of being both organisms and ecosystems. We are holobionts – consortia of numerous species integrated into our physiology, immunity and development (Gilbert et al. 2012; McFall-Ngai et al. 2013). But as biology becomes a science of processes, of becoming (see Gilbert and Epel 2015; Nicholson and Dupré 2018; Fusco 2019), it demands a different mode of drawing. Perhaps, it needs a 'romantic mode', a perspective that uses intuition to connect processes that had been considered distinct.

Indeed, Figure A.1A is a figure that one of the authors of this essay (S. F. Gilbert) is commissioning for the next edition of his developmental biology textbook. Here, symbiotic bacteria are necessary for the life cycle of the sponge *Amphimedon*. A metabolic cycle, a life cycle and symbiosis are integrated into a common scheme. The bacterial symbionts make the chemical compounds needed for the sponge larvae to synthesize nitric oxide (NO), the chemical signal necessary for initiating their metamorphosis. The symbiotic life cycle allowing the turning of the host life cycle is a diagrammatic scheme that had been drawn for a previous paper (Figure A.1B).

Drawing a biology of process has had its proponents and even some remarkable examples. Waddington's epigenetic landscape (as described and interpreted by two chapters in this volume) is an amazing epistemological illustration (Squier 2017). Even Charles Darwin's 'tree of life' can be seen as a diagram that represents processes. Darwin thought so, saying that just as new life arises in the buds of trees, so new life emerges from existing life forms, the green and budding twigs representing existing species (Darwin 1859). Moreover, even *processes* have homologies and isomorphologies (*qua* Anderson-Tempini) with other processes. One of these is evolution. Even before Darwin had popularized his famous sketch of the bifurcating lineages of animals, August Schleicher had proposed a *Stammbaumtheorie* of language evolution and had drawn trees showing the bifurcation of Indo-German languages (Schleicher 1853). Tree diagrams have also been used to show the evolution of religions (Gilbert 2003), and are similarly based on documentary evidence, homologies and the retention of unused structures. Similarities in developmental

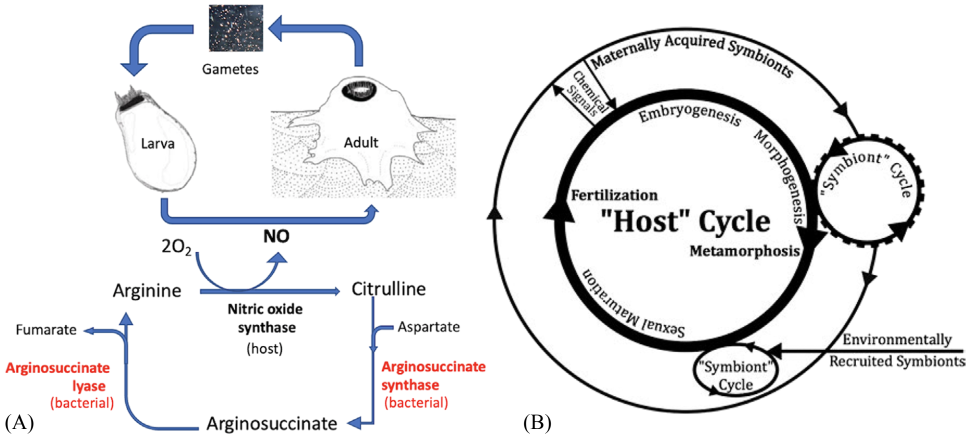


FIGURE A.1A and B: Holobiont life cycles. (A) A sketch integrating the life cycles of the sponge *Amphimedon* and its bacterial symbionts (modified from Song et al. 2021). Note the arrows designating the life cycle processes (above) are merged with the arrows denoting the biochemical processes (below). (B) A conceptual diagram for integrated host and symbiont life cycles (drawn by David Gilbert and published in Gilbert 2017).

processes have shown that the pathway by which segments form in *Drosophila* is isomorphic to the pathway by which the anterior–posterior axis forms in the roundworm, the dorsal–ventral axis forms in frogs and the initiation of certain cancers in humans (Gilbert and Bolker 2001; DiFrisco and Jaeger 2021).

Hence, not only can genes, cells and organs be considered homologous but so can processes. Not even the gene is outside of flux. The DNA gets renewed at each cycle of replication, and what DNA is a 'gene' is a matter of cellular interpretation (Stotz et al. 2006; Stamatoyannopoulos 2012). Seeing life as an evolving set of processes, including metabolism, life cycles and symbioses, is a way of seeing life wherein the organism, the cell and the genome are in flux and whose component parts are entities that are made through the concrescences of numerous processes. Perhaps a more appropriate name for Gaea would be that of her Titanic daughter, Rhea, 'she who flows'.

Drawing as a partnership to liberate both scientists and artists

If scientists now know that what we call 'organism' and 'environment' are actually inextricably enmeshed as a process of continual and contingent co-construction, then why do so many of us still tend to feel like those all-too-human individual organisms? If heterogeneity and flux are fundamental to our very biological functioning, why don't we experience these sensations more consistently, as elemental throughout everyday life?

Turning to aesthetics, we might begin by reorientating towards questions of the sensible and 'the power that inhabits the sensible prior to thought' (Ranciere and Djordjevic 2004: 2). For the French philosopher Giles Deleuze, thought, in its proper sense, cannot be individually conceived of or represented, because it does not emanate from, or belong to, any single subject. Emerging relationally in all the fleeting contingencies of lived experience, it can only be *sensed* or *felt* (Deleuze 1968/1994). This distinctly *asubjective* approach to sensation and relational thinking invites us to consider the many fecund sites of potential co-construction we might be overlooking (and neglecting to nurture) in our deep-rooted presumptions around individual agency and autonomous subjectivity.

Indeed, Kant's Copernican revolution in thought made subjectivity 'logically compatible' with scientific reason *precisely* by rendering questions of feeling irrelevant or, at the very least, an afterthought: before all else, subjectivity was presumed to be rational, structuring and ordering the world prior to our experience of it. What we lost, in what Whitehead calls this 'bifurcation of nature' (1920), is nothing less (and quite a bit more) than what aesthetics, as distinct power of thought, aims to recentre: rich worlds of affective potentialities epistemologically devalued and left unexamined, simply for want of being measurable or otherwise directly accounted for by known physical laws. For practitioners committed to the study of changing life, (re)opening the sensible as a legitimate site of epistemological inquiry could hardly be more urgent.

'The release from scientific restraints in artistic practice', say Anderson-Tempini and colleagues in this volume, 'makes collaborative image-making an open-minded experience that can be mutually beneficial for scientist and artist alike'. She and the Wakefield laboratory scored the orchestration and choreography of mitosis in several different types of cells, linking intuitive feelings and quantitative data. Musical metaphors, including that of dance, have been used to describe cell biology before (e.g. Gilbert and Bard 2014; Noble 2016), but this was probably the first time they were taken seriously enough to actually make a physical model of a physical cellular process. The changing amounts of energy dedicated to each process determined the shape of the vessel at any moment. The 'final' result, 'Garden of Forking Paths. Mitosis Score no. 5', shows mitosis *as* the cell, where the processes *are* the parts. As Yeats (1929) asked, 'How can we tell the dancer from the dance?'

There were calls and responses, and mutual inductions where exchanges were made between the drawings, the artist and the scientists. Imagination was added to the data and to the conventional imagery. As the artist and scientist found ways to represent processes, the diagrams generated new questions involving the relationship of energy to mitosis. The drawing and verb-making exercises slowed down the science and gave scientists the opportunities to think about what they did not know. Drawing is seen as a technique of liberation. James Wakefield has likened it to slow food, echoing Isabelle Stengers's idea of 'slow science' (Stengers 2018). Slow science, like slow food, he notes, takes time, care and relationships.

But from what are they liberating scientists? The enslaver, according to Waddington (1977), is an overarching fiend called COWDUNG. This is an acronym for the Conventional Wisdom of the Dominant Group. Its power comes from its being the source of funding, prestige and employment. So, as John Dupré remarked in the symposium talks, one must be very wary in one's dealings if you have evidence against it. COWDUNG holds that the arts (and artists) are peripheral (if not harmful) to science,[2] that reductionism is the sole ontology and epistemology of science, and that having fine motor skills is unimportant to their scientific inquiry (Root-Bernstein and Root-Bernstein 2013; Hill 2018).

COWDUNG also defines the boundaries of what is professionally acceptable, and as Anderson-Tempini noted, partnerships between artists and scientists are a way of liberating both the scientist and the artist from such conventions. Such collaborations have indeed been helpful in giving scientists new perspectives, outside their established terrain, and they have also allowed artists to see things never before depicted. Agassiz, for instance, was wealthy enough to afford the services of a cadre of artists such as Henry James Clark and August Sonrel (Blum 1993).[3] The drawings of microscopic turtle embryos show parts of the turtle's developmental anatomy (such as the carapacial ridge that initiates shell development in the dorsal dermis) that were only named in the 1980s (Burke 1989).

Perhaps even more fruitful for science was the partnership of biologist Christian Heinrich Pander and artist Eduard d'Alton. Although Pander is often credited with the discovery of the three germ layers of the early vertebrate embryo – the ectoderm, mesoderm and endoderm – it was his artist, d'Alton, who first visualized and meticulously drew these as-yet-unnamed structures. Pander's embryology of the chick was the best done to that date and d'Alton's drawings were critical in making it so important (Wessel 2010). Historian Frederick Churchill (1991: 4) has noted the 'mismatch between that which Pander covered in his account and that which d'Alton illustrated'. Whereas Pander gave a rough description of heart development, d'Alton deftly portrayed the chambers of the heart, the three aortic arches, the sinus venosus and the fusion of the dorsal aorta. d'Alton also drew the incipient brain bulges that we now know to be the telencephalon, diencephalon and mesencephalon. Pander did not comment on these regions nor did he recognize their distinctions; but the artist saw them to be distinctly present. Priority of discovery of the aortic arches and brain vesicles might better be given to the artist who saw them rather than to the later scientists who named them. From Pander and d'Alton onward, Churchill concludes that embryology was to become heavily dependent on its pictorial representations.

Another remarkable collaboration showed the interactions of microtubules and chromosomes during cell division, the processes that were modelled by Anderson-Tempini. These processes were gloriously revealed in the book that brought photography into embryological illustration, *An Atlas of Fertilization and Karyokinesis of the Ovum* (1895). These photographs were the collaboration of developmental biologist E. B. Wilson and photographer Edward Leaming (Wilson and Leaming 1895). Noting that van Beneden and Neyt had published photographs of roundworm embryos, Wilson claimed that Leaming's photographs were far superior since they were from his microscopic sections, rather than from whole-mounts. By photographing thin sections of sea urchin eggs, Wilson and Leaming were able to show the interactions of the chromosomes with protein fibres (the microtubules) during fertilization and mitosis. In addition to these photographs, Wilson placed camera lucida drawings of the same slide as the photograph to provide labels and explanatory captions (Figure A.2). In his preface, Wilson notes that knowledge of fertilization and cell division must 'be acquired from text-books in which drawings are made to take the place of the real object'. He quickly adds, however, 'But no drawing however excellent can convey an accurate mental picture of the real object'. And while the best drawing 'embodies a considerable amount of interpretation', the photograph at least gives 'an absolutely unbiased representation of what appears under the microscope'. There are faults with photographs, to be sure, but 'they are faults of omission rather than commission'. In his 'Note on Photographic Technique', Leaming mentioned explicitly that no retouching of the plates was performed. It was in this book that DNA was proposed as the physical carrier of inheritance and that the endoplasmic reticulum was seen to join the nuclear envelope to the cell membrane. A year later, Wilson would use such

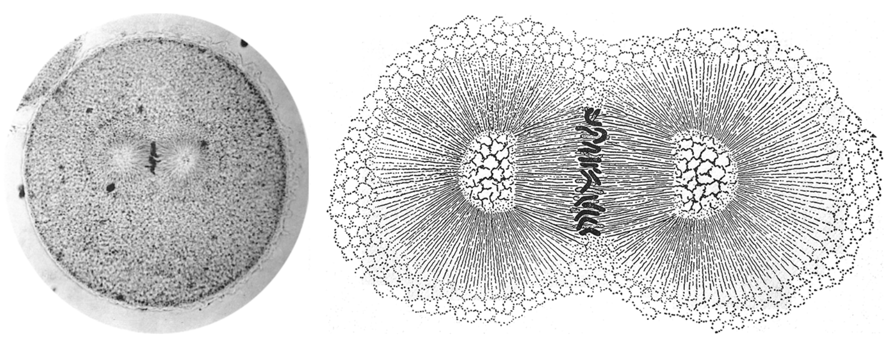


FIGURE A.2: Phototype 26 (left) of Wilson and Leaming (1895) with its accompanying diagram (right), showing the chromosomes of sea urchin zygote forming an equatorial plate in the centre of the cell. The 'astral rays' (microtubules) are seen to connect to chromosomes and to the outer cytoplasm.

drawings in his groundbreaking volume, *The Cell in Development and Inheritance*. So here, too, new artistic techniques were used to help forge a new science. And the depictions of mitosis led the way.

And, as has been mentioned in these papers, the epigenetic landscape was first presented as an interaction between biologist Waddington and his good friend, the artist John Piper. In this volume, K. Lee Chichester explicates how Waddington came to see art and biology as syncytial creative processes and believed that Action Painting (in the manner of Jackson Pollock) was a way for scientists to free their imaginations as well as their bodies. Waddington, after all, joined embryology, evolution and genetics into a synthetic field he called 'diachronic biology', a biology of change and process that we would now call 'evolutionary developmental biology' (Waddington 1975; Gilbert 2000). Moreover, he also invented the term 'homeorhesis', whereby cells on this landscape retain their developmental trajectories despite perturbations, keeping their identity while changing their metabolisms. Adult cells may have 'homeostasis', but cells in the processes of developing must express homeorhesis (Matsushita and Kaneko 2020). New ideas in biology need new representations and new images. The field of developmental genetics needed a diagram that would integrate genetics into a developmental framework, indeed a framework wherein the genes helped control developmental processes. The epigenetic landscape was the model that gave the data new meaning (Borish and Gilbert 2016; Nicoglou 2018).

Gardens of forking paths: Isomorphic pathways of cells, proteins and philosophy

In this volume, we find separate papers that have isomorphic properties. The path on which cells acquire their fate, the path on which proteins acquire their form and the path by which investigators find their provisional truths appear to be the same, or at least, homologous pathways.

Let us say at the outset: 'Nothing in cell biology makes sense except in the light of protein folding'. Whether it's enzymes and their substrates, antibodies and their antigens, hormones and their receptors, sperm binding proteins and the egg recognition sites, signalling pathways, DNA synthesis or protein synthesis, it's all about the interlocking shapes formed by protein folding (Gilbert and Greenberg 1984). Protein folding determines binding-specificity and, where needed, catalysis. There is a sculptural dimension to this protein folding. Terrence Deacon, in his analysis of absence (Deacon 2012: 9), points out that 'hemoglobin is exquisitely shaped in the negative image' of the oxygen molecule it will carry, 'like a mold in clay'.

What is striking about Gemma Anderson-Tempini's presentation is the similarity of protein folding to embryogenesis. This was a synthetic idea that goes back to the early era of phage genetics, where the intricate coordination of viral proteins and nucleic acids was (and is still) described as a morphogenetic process (e.g. Israel et al. 1967; Benler et al. 2020). First, Anderson-Tempini has commented on the similarity of the funnel diagrams of protein folding to Waddington's model of the epigenetic landscape, which is not unlike her mazes on a cone. These topologies are used as developmental landscapes. It is also interesting that Waddington's original notion of epigenesis (before he and Piper made it a 'landscape') was one of the sequential cones, where the cell would fall into more stable states until it was finally at rest (Needham 1936).

Second, when Anderson-Tempini, Verd and Jaeger use 'drawing to extend Waddington's epigenetic landscape', they do so by forming models that look remarkably like the protein folding diagrams of Jane Richardson. Their 'Somitogenesis/Oscillations Knot', for instance, looks like an alpha-helix folded in on itself. Remarkably, the Kline bottle model presented in their conclusion is very much like a properly folded protein, with its structure stabilized by the different levels of noise on the inside and outside of the bottle. The Kline bottle model is also an Ouroboros, a figure that Waddington repeatedly doodled and even reprinted in an autobiographical statement (Waddington 1975; Ingram 2019).

Third, the models that are proposed for both the epigenetic landscape and protein folding are models wherein the interacting parts 'seek' their lowest energy levels. The thermodynamic stability of the protein folds is very similar to the 'basins' of gene regulatory networks that represent the resting states of cell differentiation (Huang 2009).

In both of these cases, protein folding and cell fate determination, we see a process very similar to the one that Chiara Ambrosio ascribes to Charles Sanders Peirce. Here, the concept of inquiry is paramount, and drawing can be seen as a method of taking one from a position of irritation and doubt to a healthier position of temporarily settled belief. In other words, one goes from the pluripotent and disturbed condition to a singular secure position. Dr Ambrosio shows that Peirce used diagrams throughout his lectures, and she analyses Pierce's trope of the serpentine line and the brick wall in his 1903 lecture at Harvard. The serpentine line traces the path from perception to an 'abductive inference', a conclusion that was the best plausible explanation available, but which was not proven beyond a reasonable doubt. In his critiques of perception, Peirce loops a serpentine line around itself to make what looks like a brick wall. The line and the wall are both possible, and both are judgements. They are equilibrium positions, not unlike the equilibrium position of a folded protein or a stable cell type.

And the intellectual quest may be another example of such attempts that start with doubt and travel through various pathways before reaching relative certainty and calm. Dr Ambrosio's use of Richardson's diagrams is wonderfully Peircean: What is sometimes difficult to see in the complex foldings of the helices and sheets is that the protein is actually a linear array of amino acids. The protein is Peirce's serpentine line, and it has the ability to fold in several ways. It is the ideal example of a pragmatic drawing epistemology. Morange (2011) has written that Richardson's investment in the ribbon diagrams had three sources: (1) an interest in the evolutionary classification of proteins; (2) the view that data representation was as important as data accumulation and (3) her sense of aesthetics, and her ability to see patterns between highly divergent objects. It should also be noted that Richardson's BA from Swarthmore College is in philosophy, where she was attracted to the pre-Socratics and Spinoza. She spent a year as a graduate student in philosophy before deciding it was not for her (Roseberry 2007).

Moreover, in providing the drawings done along the pathway to her final drawings of folded proteins and epigenetic landscape, Anderson-Tempini is showing the morphogenesis of the model, as it interacts with her own art. The art and the science become mutualistic partners, and the path in the morphogenesis of these models is shown by their succession of embryonic forms. Anderson-Tempini alludes several times to Kaufmann's model of 'The Adjacent Possible'. Only certain things can transform into others, depending on what possibilities are open and which are closed. This idea can be derived from the epigenetic landscape, and Kauffman shows that novelty becomes possible when adjacent modules can interact with one another. And perhaps Anderson-Tempini's bringing together artists and scientists is precisely designed to create new adjacent possibilities. Taking a protein through a maze from native protein to stable protein becomes a social interaction, a 'drawing lab', where people pool their knowledge and their imaginations. The image becomes interactive through the drawing process, and there are many routes to the same end. As Anderson-Tempini notes, the maze becomes a mandala, which, like the sand mandalas of Buddhist artists, are collective creative endeavours that invite meditation and reflection.

Anderson-Tempini's fascinating idea of a fluid maze links protein stability with flux. It would be interesting to use this idea to model the changes in conformational states that a protein assumes when it binds to its partners. Such binding is said to be 'induced fit' rather than 'lock-and-key', indicating that there are stable changes that are made that are critical for protein functions (Koshland 1995). This may also indicate why chaperone proteins are needed to keep the signal transduction proteins in functional states. These chaperone proteins are often thought of as nurses or aid-givers to help proteins fold properly. Seeing them (as Anderson-Tempini and colleagues do) as trained yoga instructors may give us new appreciations of their functions. As Jonathan Philips mentioned in his chapter, even the act of vision demands that the maze shifts as the photons interact with the retinal proteins. And if we are willing to employ the metaphor of 'chaperones' to stabilizing proteins, why not 'yogis'?

Philips also mentioned that the interactive and social modes of drawing provided a new, 'intuition-first' rather than 'maths-first', entry into the scientific field. Protein folding has a high barrier of initiation caused by physical chemistry and mathematics. The artistic model builds on exploration and randomness. As he said in the discussion, the students 'are being the protein in a way'. Also importantly, Anderson-Tempini mentioned that each drawing was an experiment. As artists know, each trial of art is an experiment; it involves conceptualization, execution and interpretation. And like most scientific experiments, most paintings, most ceramic bowls and most glass vases get thrown into recycling bins.

A caring for the organism

There are many worlds on this planet. The worlds of the amoeba or sperm are not the world we live in. In addition to each organism having its own perceptual *Umwelt*, different animals and cells actually live in different physical universes. How to render these universes palpable to us *Homo sapiens* is a formidable task for art and science. It takes us from 'matters of fact' to 'matters of concern', something capable of a science slowed down and made observant through art. Latour (2004: 232) has asked, 'Can we devise another powerful descriptive tool that deals this time with matters of concern, and whose import then will no longer be to debunk but to protect and care, as Donna Haraway would put it?' One tool may be an artscience whose goal would not be merely to understand but also 'to protect and care for matters of concern' (Stengers 2017).

In such artscience, experimental staging is crucial and would consist of invitations for collaborative organisms. The organisms would therefore be partners who work with the scientists who eventually would speak for them. This is not a futuristic concern. Such collaborations have recently been accomplished in the restoration of the Chesapeake Bay. For over a century, the rallying cry of environmentalists had been to save the oyster from extinction. However, when scientists found that the oyster had the ability to filter the waters of the bay and degrade its pollution, the cry became 'Save the bay – plant oysters'. The oysters became partners with the conservationists (Gilbert 2019). More recently, oysters are being enrolled as partners to restore the Hudson estuary by forming living breakwaters around Manhattan. The project is only half-jokingly called 'Oystertecture' (Wakefield and Braun 2019; Klineberg 2021).

The terms 'artscience', 'oystertecture' and others are kin to Donna Haraway's (Haraway 2003) 'natureculture', the absence of boundaries between the 'natural' and the 'human'. As Chakrabarty (2009: 201) proclaimed, in the Anthropocene, one sees 'the collapse of the age-old humanist distinction between natural history and human history'. This collapse means a great deal for art. Heather Barnett spoke on the wondrous abilities of slime moulds to explore space (and time) such that it makes cost-effective decisions on where to proliferate and extend. *Physarum polycephalum*, an acellular slime mould, wherein thousands or millions of nuclei co-exist within a common enormous cytoplasm, was given invitations to explore new environments. Here, these moulds were able to find the shortest path through complex mazes (Nakagaki et al. 2007; Reid and Beekman 2013). They optimized their cell shape, vein network and growth according to external stimuli. Barnett emphasizes the role of *Physarum* as co-creator of their artwork, forming a sympoietic relationship across kingdoms in order to create something novel. Co-creation mandates collaborative and hybrid techniques and methods of playing between the size and time scales at opposite ends of the living spectrum. Barnett's experiments are also artistic inquiries, and this method of revelation employs 'hybrid artistic and scientific methods'. The word 'hybrid' indicates a fusion of art and science into a single agency.[4]

One example of care is to respect the world that cells or organisms live in and to appreciate what entanglements they may struggle with. Part of our anthropocentrism comes from our expectation that the rest of the planet lives at high Reynolds numbers, as we do. Those of us cognizant of living in a high Reynolds number world, where gravity dominates over viscous forces, need to understand that while we may share the same planet, even the same acreage, as slime moulds, insects and microbes, we inhabit different worlds. Even the cells of our body inhabit a different world than our body does, an *Umwelt* of haptic and chemical sensation, where viscous forces play a far greater role than gravity. To create relational encounters between humans and an acellular slime mould, to technologically and artistically mediate interactions between phyla whose sense of time and space may be unrecognizable from ours, is to meet sincerely with an organism as foreign from humanity as one might imagine. The notion of process is underwritten by the temporal dimension, the '/dt' term. So what is the process of an organism who senses time and space differently than we do and how can artistic technology translate the stories of *Physarum* into a human consciousness?

Although *Physarum* is neither an animal, a fungus, nor a plant, there are things we share. The movements of *Physarum*, the contractions and extensions of its cytoplasm, are based on the activation of protein fibres by calcium ions. Indeed, such calcium-activated protein activation is also found in humans. This calcium-mediated changes in cytoskeletal proteins (a wonderful example of protein folding at work) causes the beating of our hearts as well as the movement of the human sperm and the activation of the egg (Panfilov 2017; Barresi and Gilbert 2019). These calcium-induced waves establish the rhythms of mitosis. It would be interesting to back up a moment and look at the calcium-induced waves as creating both the human and the slime mould. Perhaps we can co-create because we have the same equipment in our toolboxes. Barnett has shown that the combination of art and science can help us grok the *Umwelt* that pervades our soils and ocean floors, respecting the world and world-view of our very significant others.

The importance of artscience for care is also demonstrated in James Wakefield's manual for depicting cellular objects. There is no such thing as an uninterpreted cell (Gilbert and Braukman 2011), and 'attending' is critical to a proper interpretation. This attending can include drawing exercises and rituals to focus the attention of the mind as well as the lenses of the microscope. Science is a craft, and the repetition of crafting processes and the feel for the material one works with allow for creativity (Gilbert 2018). Indeed, they help cultivate the heightened corporeal awareness that Deleuze called 'the apprenticeship of the unconscious'. Art can help slow science, make it more responsive and make it more accurate. As Pirsig (1974: 206) had noted, 'Assembly of Japanese bicycle require great peace of mind'.

And sometimes Nature is the consummate artist. As Wahida Khandker has pointed out in this volume, few phenomena show nature's 'artistry' better than mimicry and crypsis (we conflate crypsis, masquerade and transparency as modes of avoiding being seen). As James Wakefield pointed out, mimicry can be physiological or evolutionary. The physiological mode is active, while the evolutionary mode is a passive mode wherein those organisms that look enough like the model organism have a higher probability of not being eaten. While *Physarum* is obviously moving towards a target (i.e. food), those organisms that evolutionarily mimic another organism or attempt to remain hidden in the environment are also 'moving' towards a goal, if only metaphorically. They are climbing up the fitness peaks on the adaptive landscape. While sperm and slime moulds show their goal-directed behaviour by physical movement, those animal lineages evolving towards mimicry or crypsis have a goal that is something else – a poisonous butterfly, a dead leaf or any other item that would allow them not to be seen as prey. The slime mould and sperm (and, for that matter, the cuttlefish) can move to their goals physiologically; the animal lineage heading towards mimicry or crypsis moves evolutionarily.

Nature's art and improvisational skills are seen when changes in the environment cause changes in the camouflage. When eggs of the moth *Nemoria arizonaria* hatch on oak trees in the spring, the caterpillars resemble the seed catkins of the oak trees. However, when they hatch in the summer (when the catkins are gone), they resemble young branches. The leaves (which are full of tannins in the spring) appear to control which shape, colour and texture are produced. Similarly, the butterfly *Bicyclus anynana* has two adult phenotypes. The dry (cool) season morph is a mottled brown butterfly that survives by resembling the dead leaves of the forest floor. The wet (hot) season morph, which routinely flies, has large ventral spots that resemble eyes and which deflect bird and lizard attacks (Brakefield and Frankino 2009; Prudic et al. 2015). The patterns and colours are determined by a heat-sensitive expression of the hormone ecdysone, which, if expressed at high levels, induces the eyespot and other warm-season changes (Brakefield et al. 1996; Oostra et al. 2014).

Artscience allows us to use both biological and artistic knowledge and technologies to allow us to *feel* the integration of organism and environment on a greater-than-intellectual level. It allows us an affective as well as rational means of apprehending the world. Watts (1970) and Sagan (2004) have argued that while biologists and physicists intellectually know that the organism and the environment are not two separate things – but are rather a single process, a unified field – they don't necessarily *feel* that this is so. This is what artscience can do. It can help us slow down, feel and even care. Artscience could create what Stengers calls 'ambulent practitioners', scientists who saunter rather than march, and who would notice, care and let themselves be intrigued (Stengers 2020). Such ambulant, 'earthly' scientists would integrate their knowledge with 'a set of collective non-scientific activities' to do the very practical work of generating a science where matters of earthly concern predominate over those of abstract rationality. Human exceptionalism would have no place in such a view of life, wherein organism and environment are constantly generating each other. The art of the artscience would convey the affective as well as the intellectual modes of the science partner. Indeed, in one of the first uses of the word 'artscience' (Root-Bernstein et al. 2011: 63), it is characterized as 'integrative collaboration to create a sustainable future'.

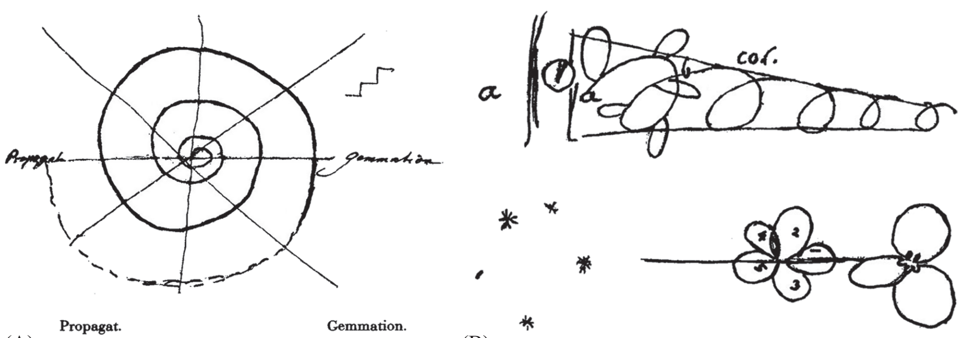
Coda: Goethe's *aperçu*

Such integration of art and science, rationality and imagination brings us to Goethe and Romantic Biology. Janina Wellmann (Wellman 2017) and Gemma Anderson-Tempini (Anderson-Tempini 2019) have written about Goethe's theories of organic motion and his 'gentle empiricism'. James Wakefield also mentioned Johann Wolfgang Goethe, for whom intuition, poetry and music were as important to the scientific enterprise as observations and mathematics (Richards 2002). Goethe's ideas of aesthetics and metamorphosis were critical to the art-science collaboration of Pander and D'Alton, mentioned earlier (Schmitt 2005). Figure A.3A presents Goethe's hand-drawn image of a plant's life spiral. That's not 'life-cycle (*Lebenszyklus' Lebensgeschichte*) but '*Spirale*'. Circles are complete and perfect; life isn't. Mathematically, the circle is merely the bounded collapse of the spiral. It is complete, but life goes on.

In his 1829 *Zeichnung zur Spiraltendenz der Vegetation*, Goethe claimed that plants have a *Spiraltendenz*, a spiral tendency, alternating between asexual budding (gemmation) and sexual seed reproduction (proliferation) as they grow (Goethe 1829). Thus, plants had agency, and they were actively productive. This is beautifully represented by the dotted line of the spiral, which has yet to come. By linking life patterns to activity, Goethe was able to show his dynamic life history for plants and was able to free his explanations from the norm, which had emphasized their teleological aspect and their place in God's creation (Rupik 2021).

Goethe's theory of development demanded that the eyes of the body (taking in the particulars) and the eyes of the mind (knowing the model) had to act together to synthesize how the plant develops (Klausmeyer 2021). Goethe came to this notion of spiral tendency with botanist Karl Friedrich Philipp von Martius in 1828, who noted the spiral paths of leaf formation on new stems. Goethe appeared to be happy to subsume his earlier work into the grander all-encompassing spiral model of plant development. In his late works in plant development, Goethe insists, 'We must assume that a universal spiral tendency presides in vegetation through which, in connection with vertical striving, every structure, every formation of plants, is achieved according to the law of metamorphosis' (Goethe 1828). The result is a plant that has a helical structure (Figure A.3B).

The spiral line is Goethe's 'line of love', the line of affinity and the line of embracement. Goethe called the tendency to form spirals the 'basic law of life' (Müller and Tsuji 2017). Mainberger (2010) has written that 'the spiral' became a kind of intersection point of the author's aesthetic and scientific interests, including the vitality of youth, eroticism, dance, physiognomy and even death. (In July 1831, Frederic Soret wrote that 'He is more than ever obsessed by the spiral tendency'. Goethe



(A) (B)

FIGURE A.3A and B: Goethe's spiral and helix. (A) Spiral of plant life passing through gemmation (asexual reproduction) and prolifikation (sexual seed production) from his *Zeichnung zur Spiraltendenz der Vegetation* (1829). (B) Helical growth of plants from J. W. Goethe and K. F. P. Martius's *Zeichnungen zur Erläuterung der Spiraltendenz der Vegetation* (1828). From Klausmeyer (ref. 55).

died within that year.) This spiral line represents open-endedness and possibilities. It is unbounded, yet it shows prior history and constraints. It is returned with a difference. Interlocking spirals symbolize enmeshment, even life, and it may be an excellent form to represent the integrated life cycles of symbionts.[5] The spiral and helix are primary forms in nature. A human sperm, for instance, swims in a spiral fashion towards the egg. Moreover, in addition to carrying a set of double helices in its haploid nucleus, the midpiece of the tail also contains 'a double-helical structure called the mitochondrial sheath'. This sheath of mitochondria wraps produces the energy for human sperm propulsion (Hirata et al. 2002). In addition, at the tip of the tail, connecting the microtubules to the cell membrane is a helix, 'the tail axoneme intra-luminal spiral' that may help sperm swimming by preventing microtubule disassembly (Zabeo et al. 2018). That's four sets of spirals for the sperm.

Perhaps spirals (and their three-dimensional helices) can be used to represent the interacting lineages that form holobionts, and this representation can be used in attempts to model the five-dimensional organism of evolutionary developmental biology (the three physical dimensions, developmental time and paleontological time). Spirals and helices, derived from Goethe's model and from modern science, can symbolize the rule-bound, incomplete and open-ended growth that is open to experimentation with environmental change. Indeed, new depictions of the evolutionary history of the earth may be expanding from tree models to those of networks and spirals (Ricou and Pollock 2012).

One such model, consciously constructed to represent intersecting life cycles and anti-essentialism is Ursula K. Le Guin's 'Heyiya-if', a set of interlocking spirals (Figure A.4). This symbol is seen in many permutations throughout *Always Coming Home* (Le Guin 1985), where it structures the lives, architecture, music,

FIGURE A.4: A Heyiya-if, a diagram representing interlocking lives from Ursula K. Le Guin's *Always Coming Home*. Original by M. Chodos-Irvine; made available from Creative Commons.

poetry and philosophy of the Kesh people. This interlocking spiral motif is also seen in art, at least as ancient as the tomb of Egyptian queen Nefertari (died *c.*1255 BCE), on whose tiles this design is wrought. It can be formed by cupping one's fingers into the palm of the opposite hand. Such an accessible form might be a fitting diagram for what it means to be holobiont.

Biology and its representations have a positive feedback on each other. As changes in science demand changes in its representations, the newly formed representations will promote and stabilize only those particular perspectives of the science. They would enable new questions to be asked and would also channel the mind into these new directions. Representations are both creative and constrictive. Therefore, one representation should not be thoroughly hegemonic. Indeed, Stengers (2018) contends that if science could free itself from its current mercantile model, it would develop into multiple modes of science. Such a pluralistic biology would have multiple modes of representation. Recognizing the mutualistic symbioses between biology and art may help bring about such new ways to depict biology as a process. This book is an embryonic landmark on the way to such representations.

ACKNOWLEDGEMENTS

We wish to thank Gemma Anderson-Tempini, Chiara Ambrosio and Caroline Jones for their helpful comments on earlier drafts of this essay.

NOTES

1. It is now known as the Harvard Museum of Comparative Zoology. Agassiz's name is being dissociated from many monuments due to his attempts to justify racism through science. Some of these attempts used art, specifically photographs of naked Brazilian slaves. In a recent symposium concerning, these photographs, de la Fuente (2021) noted, 'Artists are protagonists in this process of knowledge production'.
2. Drawing, painting, music and dancing are neither luxury items nor educational peripherals. Rather, empirical evidence shows them to be critical, perhaps mandatory, parts of scientific education. As Michèle and Robert Root-Bernstein (1989, 2013) have shown, art background and success in science have an almost linear relationship. 'The more arts and crafts that scientists, engineers, and entrepreneurs engage in across their lifetimes, the greater the likelihood of achieving important results in the workplace' (Root-Bernstein and Root-Bernstein 2013). Indeed, the best predictors of whether a college student will succeed in mathematics and science are their scores on visual imaging and visual memory tests (Winner and Casey 1992). On these tests, students who excel in the sciences outperform art majors.
3. Sonrel became a major photographer in the remarkable city that was Boston in the 1860s and 1870s, making *carte de visit* portraits for the likes of Oliver Wendel Holmes (both

senior and junior), sculptor Anne Whitney, mathematician Benjamin Peirce (Charles Peirce's father), and Louis Agassiz and his wife.

4. Biologically, 'hybrid' indicates a complete fusion between two entities, whereas 'chimeric' indicates that the two entities have come together but retain their separate characters. Classes that are simultaneously live and online are really 'chimeric', not 'hybrid'. One of the authors (S. R. Gilbert) of this book has co-constructed art with bark beetles, whose curvilinear tubes in tree branches were used to inform musical notes on a player piano. New installation-like mesocosms are now being created as a middle ground between the uncontrolled natural environment and the regimented conditions of the laboratory. This allows substantial cooperation with the more-than-human.
5. The spiral of life metaphor is also used in Suzanne Simard's *Finding the Mother Tree* (Simard 2021), which is largely about the critical importance of symbiosis for the plant survival.

REFERENCES

Agassiz, Louis (1857), 'Contributions to the natural history of the United States. Part III', *Embryology of the Turtle*, Boston: Little, Brown, and Co.

Anderson, Gemma (2019), *Drawing as a Way of Knowing in Art and Science*, Bristol: Intellect.

Ankel-Simons, Friderun and Cummins, Jim M. (1996), 'Misconceptions about mitochondria and mammalian fertilization: Implications for theories on human evolution', *Proceeding National Academy of Sciences USA*, 93, pp. 13859–63.

Barresi, Michael J. F. and Gilbert, Scott F. (2019), *Developmental Biology*, 12th ed., New York: Oxford University Press.

Benler, Sean, Hung, Shr- Hau, Vander Griend, Jacob A., Peters, Gregory A., Rohwer, Forest and Segall, Anca M. (2020), 'Gp4 is a nuclease required for morphogenesis of T4-like bacteriophages', *Virology*, 543, pp. 7–12.

Blum, Ann S. (1993), *Picturing Nature: American Nineteenth Century Zoological Illustration*, Princeton: Princeton University Press.

Bonner, John T. (1965), *Size and Cycle: An Essay on the Structure of Biology*, Princeton: Princeton University Press.

Borish, Steven and Gilbert, Scott F. (2016), 'Waddington's epigenetic landscape', in R. M. Klinman (ed.), *Encyclopedia of Evolutionary Biology*, vol. 4, Oxford: Oxford University Press, pp. 349–57.

Brakefield, Paul M. and Frankino, W. Anthony (2009), 'Polyphenisms in *Lepidoptera*: Multidisciplinary approaches to studies of evolution', in D. W. Whitman and T. N. Ananthakrishnan (eds), *Phenotypic Plasticity in Insects: Mechanisms and Consequences*, Plymouth: Science, pp. 281–312.

Brakefield, Paul M., Gates, Julie, Keys, Dave, Kesbeke, Fanja, Wijngaarden, Pieter J., Monteiro, Antónia, French, Vernon and Carrol, Sean B. (1996), 'Development, plasticity and evolution of butterfly eyespot patterns', *Nature*, 384, pp. 236–42.

Burke, Ann C. (1989), 'Development of the turtle carapace: Implications for the evolution of a novel bauplan', *Journal of Morphology*, 199, pp. 363–78, https://doi.org/10.1002/jmor.1051990310. Accessed 9 November 2022.

Carroll, David M. (1996), *The Year of the Turtle: A Natural History*, New York: St. Martin's Press.

Chakrabarty, Dipesh (2009), 'The climate of history: Four theses', *Critical Inquiry*, 35, pp. 197–222.

Churchill, Frederick B. (1991), 'The rise of classical descriptive embryology', in S. F. Gilbert (ed.), *A Conceptual History of Modern Embryology*, New York: Plenum Press, pp. 1–29.

Darwin, Charles (1859), *On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life*, 1st ed., London: John Murray.

Daston, Lorraine and Galison, Peter (2010), *Objectivity*, Cambridge: Zone Books.

Deacon, Terrence W. (2012), *Incomplete Nature: How Mind Emerged from Matter*, New York: Norton.

de la Fuente, Alejandro (2021), 'Agassiz's other photographs tell a global tale of scientific racism', *The Harvard Gazette,* Cited in Aggarwal-Schifellite, Manisha *(2021)*, https://news.harvard.edu/gazette/story/2021/03/reflecting-on-louis-agassizs-lesser-known-images-from-brazil/. Accessed 25 June 2022.

Deleuze, Gilles (1968/1994), *Difference and Repetition* (trans. Paul Patton), New York: Columbia University Press.

DiFrisco, James and Jaeger, Johannes (2021), 'Homology of process: Developmental dynamics in comparative biology', *Interface Focus*, 11:3, https://doi.org/10.1098/rsfs.2021.0007. Accessed 9 November 2022.

Fusco, Giuseppe (2019), *Perspectives on Evolutionary and Developmental Biology*, Padova: Padova University Press.

Gilbert, Sarah R. (2018), 'A widening chromaticism: Learning perception in the collective craftwork of encounter', in K. A. Bull and A. Gali (eds), *Material Perceptions, Documents of Contemporary Craft No. 5*, Stuttgart: Arnoldsche Art Publications.

Gilbert, Scott F. (2000), 'Diachronic biology meets evo-devo: C. H. Waddington's approach to evolutionary developmental biology', *American Zoologist*, 40, pp. 729–37.

Gilbert, Scott F. (2003), 'Opening Darwin's Black Box: Teaching evolution through developmental genetics', *Nature Reviews: Genetics*, 4, pp. 735–41.

Gilbert, Scott F. (2017), 'Biological individuality: A relational reading', in S. Ludgard and L. K. Nyhart (eds), *Biological Individuality: Integrating Scientific, Philosophical and Historical Perspectives*, Chicago: University of Chicago Press, pp. 297–317.

Gilbert, Scott F. (2019a), 'Evolutionary transitions revisited: Holobiont evo-devo', *Journal of Experimental Zoology Molecular and Developmental Biology*, 332, pp. 307–14, https://doi.org/10.1002/jez.b.22903. Accessed 9 November 2022.

Gilbert, Scott F. (2019b), 'Shucking nature: How oysters used their material properties to save Chesapeake Bay', in Animal Materialities Symposium, Berlin, December. *Submitted to Historical Studies in the Natural Sciences.*

Gilbert, Scott F. and Bard, Jonathan (2014), 'Formalizing theories of development: A fugue on the orderliness of nature', in A. Minelli and T. Pradeu (eds), *Towards a Theory of Development*, Oxford: Oxford University Press, pp. 129–43.

Gilbert, Scott F. and Bolker, Jessica A. (2001), 'Homologies of process: Modular elements of embryonic construction', in G. Wagner (ed.), *The Character Concept in Evolutionary Biology*, New Haven: Yale University Press, pp. 435–54.

Gilbert, Scott F. and Braukman, Sabine (2011), 'Fertilization narratives in the art of Gustav Klimt, Diego Rivera, and Frida Kahlo: Repression, domination, and eros among cells', *Leonardo*, 44, pp. 221–27.

Gilbert, Scott F. and Faber, Marion (1996), 'Looking at embryos: The visual and conceptual aesthetics of emerging form', in A. I. Tauber (ed.), *The Elusive Synthesis: Aesthetics and Science*, Dordrecht: Kluwer Academic Publishers, pp. 125–51.

Gilbert, Scott F., Sapp, Jan, and Tauber, Alfred I. (2012), 'A symbiotic view of life: We have never been individuals', *Quarterly Review of Biology*, 87, pp. 325–41.

Gilbert, Scott F. and Greenberg, Jason P. (1984), 'Intellectual traditions in the life sciences. II. Stereospecificity', *Perspectives in Biology and Medicine*, 28, pp. 18–34.

Goethe, Johann Wolfgang (1829), 'Goethe. Die Schriften zur Naturwissenschaft. Vollständige mit Erläuterungen versehene Ausgabe im Auftrage der Deutschen Akademie der Naturforscher Leopoldina', in D. Kuhn, W. von Engelhart and I. Müller (eds), *Goethe-Lexicon of Philosophical Concepts*, vol. 1, Weimar: Böhlaus Nachfolger, pp. 99–112, Cited in Klausmeyer, Bryan (n.d.) 'Spirale (Spiral)', *Goethe-Lexicon of Philosophical Concepts*, https://orcid.org/0000-0002-5756-7337. Accessed 9 November 2022.

Haraway, Donna J. (1988), 'Situated knowledges: The science question in feminism and the privilege of partial perspective', *Feminist Studies*, 14, pp. 575–99.

Haraway, Donna J. (2003), *The Companion Species Manifesto: Dogs, People, and Significant Otherness*, Chicago: Prickly Paradigm Press.

Haraway, Donna J. (2016), *Staying with the Trouble: Making Kin in the Chthulucene*, Durham: Duke University Press.

Hill, Amelia (2018), 'Children struggle to hold pencils due to too much tech, doctors say', https://www.theguardian.com/society/2018/feb/25/children-struggle-to-hold-pencils-due-to-too-much-tech-doctors-say. Accessed 25 June 2022.

Hirata, Shugi, Hoshi, Kazuhiko, Shoda, Tomoko and Mabuchi, Tadashi (2002), 'Spermatozoon and mitochondrial DNA', *Reproductive Medicine and Biology*, 1:2, pp. 41–47, https://doi.org/10.1046/j.1445-5781.2002.00007.x. Accessed 9 November 2022.

Huang, Sui (2009), 'Reprogramming cell fates: Reconciling rarity with robustness', *Bioessays*, 31:5, pp. 546–60.

Ingram, Neil (2019), 'Waddington, Holmyard, and Alchemy: Perspectives on the epigenetic landscape', *Endeavor*, 43:3, p. 100690, https://doi.org/10.1016/j.endeavour.2019.08.001. Accessed 25 June 2022.

Israel, J. V., Anderson-Tempini, Thomas F. and Levine, Myron (1967), 'In vitro morphogenesis of phage P22 from heads and base-plate parts', *Proceedings of the National Academy of Sciences USA*, 57:2, pp. 284–91.

Jardine, Nicholas, Secord, James A. and Spary, E. C. (eds.) (1996), *Cultures of Natural History*, Cambridge: Cambridge University Press.

Jonas, Hans (1966), *The Phenomenon of Life: Toward a Philosophical Biology*, Evanston: Northwestern University Press.

Klausmeyer, Bryan (2021), 'Spirale (Spiral)', *Goethe-Lexicon of Philosophical Concepts*, 1, pp. 99–112, https://doi.org/10.5195/glpc.2021.22. Accessed 9 November 2022.

Klinenberg, E. (2021), 'The seas are rising. Could oysters help?', *New Yorker*, 9 August, https://www.newyorker.com/magazine/2021/08/09/the-seas-are-rising-could-oysters-protect-us. Accessed 25 June 2022.

Koshland, Jr., Daniel (1995), 'The key-lock theory and the induced fit theory', *Angewandte Chemie*, 33, pp. 2375–78.

Latour, Bruno (2004), 'Why has critique run out of steam? From matters of fact to matters of concern', *Critical Inquiry*, 30, pp. 225–48.

Le Guin, Ursula K. (1985), *Always Coming Home*, New York: Harper and Row.

Lurie, Edward (1988), *Louis Agassiz: A Life in Science*, Baltimore: Johns Hopkins University Press.

Mainberger, Sabine (2010), 'In the vortex of the spiral tendency – Questions of aesthetics, literature, and natural sciences in the works of Goethe', *Estudios Avancados*, 24, pp. 203–18.

Matsushita, Yuuki and Kaneko, Kunihiko (2020), 'Homeorhesis in Waddington's landscape by epigenetic feedback regulation', *Physical Review Research*, 2, p. 023083, https://doi.org/10.1103/PhysRevResearch.2.023083. Accessed 9 November 2022.

McFall-Ngai, Margaret et al. (2013), 'Animals in a bacterial world: A new imperative for the life sciences', *Proceedings of the National Academy of Sciences USA*, 110, pp. 3229–36.

Merian, Maria S. (1705), *Metamorphosis Insectorum Surinamensium*, Amsterdam: G. Vack.

Morange, Michel (2011), 'What history tells us XXV. Construction of the ribbon model of proteins (1981). The contribution of Jane Richardson', *Journal of Biosciences*, 36, pp. 571–74.

Müller, Stefan C. and Tsuji, Kinko (2017), 'Appearance in nature', in Tsuji, Kinko and Stefan C. Müller (eds), *Spirals and Vortices, The Frontiers Collection*, Switzerland: Springer Nature, p. 47, https://doi.org/10.1007/978-3-030-05798-5_2. Accessed 25 June 2022.

Nakagaki, Toshiyuki, Iima, Makoto, Ueda, Tetsuo, Nishiura, Yasumasa, Saigusa, Tetsu, Tero, Atsushi, Kobayashi, Ryo and Showalter, Kenneth (2007), 'Minimum-risk path finding by an adaptive amoebal network', *Physiological Reviews Letters*, 99, pp. 68–104.

Needham, Joseph (1936), *Order and Life*, New Haven: Yale University Press.

Nicholson, Daniel and Dupré, John (2018), *Everything Flows: Towards a Processual Philosophy of Biology*, Oxford: Oxford University Press.

Nicoglou, Antonine (2018), 'Waddington's epigenetics or the pictorial meetings of development and genetics', *History and Philosophy of the Life Sciences*, 40:4, p. 61, https://doi.org/10.1007/s40656-018-0228-8. Accessed 9 November 2022.

Noble, Denis (2016), *Dance to the Tune of Life*, Cambridge: Cambridge University Press.

Oostra, Vincencio, Mateus Ana Rita A., van der Burg, Karin R. L., Piessens, Thomas, van Eijk, Marleen, Brakefield, Paul M., Beldade, Patricia and Zwaan, Bas J. (2014), 'Ecdysteroid hormones link the juvenile environment to alternative adult life histories in a seasonal insect', *American Naturalist*, 184, pp. 79–92.

Panfilov, Alexander V. (2017), 'Spiral waves in the heart', in K. Tsuji and S. Müller (eds), *Spirals and Vortices, The Frontiers Collection*, New York: Springer, pp. 209–15, https://doi.org/10.1007/978-3-030-05798-5_11. Accessed 25 June 2022.

Pirsig, Robert M. (1974), *Zen and the Art of Motorcycle Maintenance: An Inquiry into Values*, New York: Harper.

Prudic, Kathleen L., Stoehr, Andrew M., Wasik, Bethany R. and Monteiro, Antónia (2015), 'Eyespots deflect predator attack increasing fitness and promoting the evolution of phenotypic plasticity', *Proceedings of the Royal Society B: Biological Sciences*, 282:1798, p. 20141531, https://doi.org/10.1098/rspb.2014.1531. Accessed 9 November 2022.

Reid, Chris R. and Beekman, Madeleine (2013), 'Solving the Towers of Hanoi – How an amoeboid organism efficiently constructs transport networks', *Journal of Experimental Biology*, 216, pp. 1546–51.

Rancière, Jacques and Djordjevic, Radmila (2004). 'Is there a Deleuzian aesthetics?', *Qui Parle*,14, pp.1–14.

Reitsma, Ella (2008), *Maria Sibylla Merian and Daughters: Women of Art and Science*, Amsterdam: Waanders Publishers.

Richards, Robert J. (2002), *The Romantic Conception of Life: Science and Philosophy in the Age of Goethe*, Chicago: University of Chicago Press.

Ricou, Joana and Pollock, John A. (2012), 'The tree, the spiral and the web of life: A visual exploration of biological evolution for public murals', *Leonardo*, 45, pp. 18–25, https://doi.org/https://doi.org/10.1162/LEON_a_00321. Accessed 25 June 2022.

Root-Bernstein, Robert and Root-Bernstein, Michèle (1999), *Sparks of Genius: The Thirteen Thinking Tools of the World's Most Creative People*, Boston: Houghton Mifflin.

Root-Bernstein, Robert and Root-Bernstein, Michèle (2013), The art and craft of science, *Educational Leadership*, https://www.ascd.org/el/articles/the-art-and-craft-of-science. Accessed 25 June 2022.

Root-Bernstein, Robert, Siler, Todd, Brown, Adam and Snelson, Kenneth (2011), 'ArtScience: Integrative collaboration to create a sustainable future', *Leonardo*, 44, p. 192.

Roseberry, Jessica (2007), interview with Jane Richardson, *Women in Duke Medicine*, 9 November, http://digitaldukemed.mc.duke.edu/med_women/women/richardson_interview.html. Accessed 25 June 2022.

Rupik, Gregory (2021), 'Ateleological propagation in Goethe's *Metamorphosis of plants*', *History and Philosophy of the Life Sciences*, 43, p. 32, https://doi.org/10.1007/s40656-021-00387-6. Accessed 25 June 2022.

Sagan, Dorion (2004), 'The postman always already rings twice', Summer, https://www.cabinetmagazine.org/issues/14/sagan.php. Accessed 25 June 2022.

Schjeldahl, Peter (2021), 'Drawing conclusions: Cézanne at MOMA', *New Yorker*, 28 June, p. 73.

Schleicher, August (1853), *Die ersten Spaltungen des indogermanischen Urvolkes*. Allgemeine Zeitung für Wissenschaft und Literatur.

Schmitt, Stéphane (2005), 'From eggs to fossils: Epigenesis and transformation of species in Pander's biology', *International Journal of Developmental Biology*, 49, pp. 1–8.

Simard, Suzanne (2021), *Finding the Mother Tree*, New York: Knoff.

Snow, Charles P. (1959), *The Two Cultures*, Cambridge: Cambridge University Press.

Song, Hao, Hewitt, Olivia, and Degnan, Sandie M. (2021), 'Arginine biosynthesis by a bacterial symbiont enables nitric oxide production and facilitates larval settlement in the marine-sponge host', *Current Biology*, 31:2, pp. 433–37.

Squier, Susan M. (2017), *Epigenetic Landscapes: Drawing as Metaphor*, Durham, NC: Duke University Press.

Stamatoyannopoulos, John A. (2012), 'What does our genome encode?', *Genome Research*, 22, pp. 1602–11.

Stengers, Isabelle (2017), 'Matters of concern all the way down', *Ctrl-Z, 7*, https://www.ctrl-z.net.au/articles/issue-7/stengers-matters-of-concern-all-the-way-down/. Accessed 25 June 2022.

Stengers, Isabelle (2018), *Another Science Is Possible: A Manifesto for Slow Science* (trans. S. Muecke), New York: Wiley.

Stengers, Isabelle (2020), 'The Earth won't let itself be watched', in B. Latour and P. Weibel (eds), *Critical Zones: The Science and Politics of Landing on Earth*, Cambridge: MIT Press, pp. 228–35.

Stotz, Karola C., Bostanci, Adam and Griffiths, Paul E. (2006), 'Tracking the shift to "postgenomics"', *Community Genetics*, 9, pp. 190–96.

Tauber, Alfred I. (2001), *Henry David Thoreau and the Moral Agency of Knowing*, Berkeley: University of California Press.

Todd, Kim (2007), *Chrysalis: Maria Sibylla Merian and the Secrets of Metamorphosis*, New York: Harcourt.

Waddington, Conrad H. (1968), *Behind Appearance: A Study of the Relations between Painting and the Natural Sciences in this Century*, Cambridge: MIT Press.

Waddington, Conrad H. (1975), *The Evolution of an Evolutionist*, Ithaca: Cornell University Press.

Waddington, Conrad H. (1977), *Tools for Thought*, Boulder: Paladin.

Wakefield, Stephanie and Braun, Bruce (2019), 'Oystertecture: Infrastructure, profanation, and the sacred figure of the human', in *Infrastructure, Environment, and Life in the Anthropocene*, Durham: Duke University Press, https://doi.org/10.1215/9781478002567-012. Accessed 25 June 2022.

Walls, Laura D. (1997), 'Textbooks and texts from the Brooks: Inventing scientific authority in America', *American Quarterly*, 1, pp. 1–25.

Watts, Alan (1970), *Does it Matter? Essays on Man's Relation to Materiality*, New York: Pantheon Books.

Wellman, Janina (2017), *The Form of Becoming: Embryology and Epistemology of Rhythm, 1760–1830*, New York: Zone Books.

Wessel, Gary M. (2010), 'Christian Heinrich Pander (1794–1865) and the concept of the three germ layers', *Molecular Reproduction and Development*, 77, https://doi.org/10.1002/mrd.21236. Accessed 25 June 2022.

Wilson, Edmund B. and Leaming, Edward (1895), *An Atlas of Fertilization and Karyokinesis of the Ovum*, New York: Columbia University Press.

Winner, Ellen and Casey, M. Beth (1992), 'Cognitive profiles of artists', in G. C. Cupchik and J. László (eds.), *Emerging Visions of the Aesthetic Process: In Psychology, Semiology, and Philosophy*, Cambridge: Cambridge University Press, pp 154–70.

Winsor, Mary (1979), 'Louis Agassiz and the species question', *Studies in the History of Biology*, 3, pp. 89–117.

Yeats, William B. (1929), 'Among school children', Finneran, R. J. (ed.) *The Poems of W. B. Yeats: A New Edition,* New York: Macmillan Publishing Company, http://poetry.about.com/od/poems/l/blyeatsamongchildren.htm. Accessed 25 June 2022.

Zabeo, Davide, Heumann, John M., Schwartz, Cindi L., Suzuki-Shinjo, Azusa, Morgan, Garry, Widlund, Per O. and Höög, Johanna L. (2018), 'A lumenal interrupted helix in human sperm tail microtubules', *Science Reports*, 8, p. 2727, https://doi.org/doi:10.1038/s41598-018-21165-8. Accessed 25 June 2022.