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Malpighi, Swammerdam and the Colourful Silkworm: Replication and Visual Representation in Early Modern Science

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Summary

In 1669, Malpighi published the first systematic dissection of an insect. The manuscript of this work contains a striking water-colour of the silkworm, which is described here for the first time. On repeating Malpighi's pioneering investigation, Swammerdam found what he thought were a number of errors, but was hampered by Malpighi's failure to explain his techniques. This may explain Swammerdam's subsequent description of his methods. In 1675, as he was about to abandon his scientific researches for a life of religious contemplation, Swammerdam destroyed his manuscript on the silkworm, but not before sending the drawings to Malpighi. These figures, with their rich and unique use of colour, are studied here for the first time. The role played by Henry Oldenburg, secretary of the Royal Society, in encouraging contact between the two men is emphasized and the way this exchange reveals the development of some key features of modern science — replication and modern scientific illustration — is discussed.

Contents

1. Introduction

In early summer 1675, Jan Swammerdam (1637–80), under the influence of his religious guru, Antoinette Bourignon (1616–80), sent a small set of detailed drawings of the silkworm to his old friend Nicolaus Steno (1638–86).[1] Swammerdam asked Steno to transmit these documents to the Italian anatomist Marcello Malpighi (1628–94), as an expression of his esteem, and as an indication that he had definit-

[1]Niels Stensen (or Nicolaus Steno as he is generally known, in the Latinized version of his name) was a Dane who had been a student with Swammerdam. For Steno's extraordinary life see Harald Moe, *Nicolaus Steno — An Illustrated Biography* (Copenhagen, 1994).

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ively abandoned what he had called 'this forbidden tree of science'[2] for a life of religious contemplation. Spreading out from this pivotal moment, up and down the timeline, there is a web of events that sheds light on the interactions between these two major figures of seventeenth-century biology and on their vision of scientific discovery.

The early history of the microscope, the role played by instrumentation in developing early biology, and the work of the key pioneers of this new science has recently been placed in its social, scientific, and philosophical context.[3] The relations between Swammerdam and Malpighi, which have never been studied in any detail, provide a fundamental insight into a period that was decisive for the development of some key features of modern science: replication, the representation of discoveries, the exchange of information, and the importance of learned societies for encouraging scientific debate and discoveries.

2. Malpighi and the silkworm

On 28 December 1667, Henry Oldenburg (1615–77), secretary of the recently founded Royal Society, wrote an official letter to Malpighi. Malpighi was already well known for his discovery of pulmonary capillaries at the beginning of the decade, which had completed the circulatory loop proposed by Harvey in the early years of the century. He had recently published a letter on the anatomy of the vertebrate tongue in the Royal Society's journal, the *Philosophical Transactions*.[4] Under the impression that Malpighi was still Professor of Medicine at the University of Messina in Sicily (a post he held from 1662 to 1666), Oldenburg asked Malpighi to 'impart to us whatever in your later work appears to be philosophically notable, or whatever occurs to other skilled and learned men in Sicily that helps to promote philosophy'.[5] In a postscript he suggested that the Royal Society would like to receive reports 'concerning plants, or minerals, or animals and insects, especially the *silkworm* and its productions, and finally concerning meteorology and earthquakes'.[6] The silkworm was presumably specified because of its economic aspects, and because it had been the subject of non-microscopic studies, in particular those of Aldrovandi (1602)[7] and Bonoeil (1622).[8]

Three months later, on 22 March 1668, Malpighi replied from Bologna, where he was now Professor of Anatomy. Malpighi enthusiastically accepted Oldenburg's

[2]Quoted in Edward G. Ruestow, *The Microscope in the Dutch Republic: The Shaping of Discovery* (Cambridge, 1996), p. 119.

[3]Catherine Wilson, *The Invisible World: Early Modern Philosophy and the Invention of the Microscope* (Princeton, 1995); Marion Fournier, *The Fabric of Life: Microscopy in the Seventeenth Century* (Baltimore, 1996); E. G. Ruestow (note 2).

[4]M. Malpighi, *Philosophical Transactions*, 27 (23 September 1667), 493.

[5]Henry Oldenburg, 'Letter to Malpighi (28.12.1667)', in *The Correspondence of Henry Oldenburg*, ed. by A. R. Hall and M. B. Hall (London, 1967), IV, 92. Lisa Jardine, *Ingenious Pursuits* (London, 1999), p. 125, suggests that Malpighi was an 'Italian Protestant working in Basle' and that his religious beliefs in some way explained the Royal Society's interest in him. Not only did Malpighi never teach in Basle, he was a Catholic: towards the end of his life, he was made the Pope's personal physician. In fact, Malpighi feared that his connections with the Royal Society might cause him problems in Italy: Howard Adelmann, *Marcello Malpighi and the Origins of Embryology*, 5 vols (Ithaca, 1966), I, 347.

[6]H. Oldenburg (note 5).

[7]U. Aldrovandi, *De Animalibus Insectis Libri* (Bologna, 1602).

[8]For Jean Bonoeil's charmingly misleading representation of silkworms (complete with human eyes, deer's antlers and bird faces) which appeared in his 'Treatise of the Art of Making Silke', see S. Peter Dance, *The Art of Natural History* (London, 1989), p. 29.

invitation, stating he was already 'investigating the internal anatomy of animals, whose parts are made with such skill and such wonderful minuteness that they escape the senses and the dull understanding of my mind' and that 'As for the history of silkworms, because our region, too, abounds [with them], I shall work on it in early spring.'[9] As his letter implied, a few months previously, Malpighi had carried out some initial insect dissections, first on a butterfly, then on the silkworm.[10] There is no evidence that Oldenburg had heard of this work, but it may have been the case.[11] Although Oldenburg had not specified what kind of study he hoped for, the result was a major scientific breakthrough.

In spring 1668, Malpighi turned his entire attention to the internal anatomy of the silkworm, focusing on the major contemporary questions: reproduction, respiration, circulation, digestion, and metamorphosis. Unlike previous illustrated studies of insect structure such as Robert Hooke's ground-breaking work of popular science *Micrographia*[12] (1665) or Francesco Redi's *Esperienze Intorno Alla Generazione Degl'insetti*[13] (1668), Malpighi opened up his insects, showing the falsity of the Aristotelian tradition that insects have no internal structures apart from the gut.

The task Malpighi set himself was far from easy. As he put it later:

> My dissertation on *Bombyx* was extremely tiring and laborious, because of the novelty, minuteness, fragility and entanglement of the parts. Carrying out the task therefore made it necessary to develop entirely new methods. And since I pursued this exacting work for many months without respite, in the following autumn I was afflicted with fevers and an inflammation of the eyes.[14]

The difficulties involved in the project should not be underestimated. The silkworm larva is about 30 mm long (the adult moth is substantially shorter), and Malpighi apparently used a single-lens microscope[15] with what today would be considered poor optics and worse ergonomics. Furthermore, the instruments and techniques required to make such dissections simply did not exist: Malpighi had to invent them. In carrying out this work, Malpighi was apparently fulfilling a comparative and reductionist project that he had nurtured since at least the beginning of the 1660s. As he had written in 1661, 'nature requires us to devote our pioneer works to simpler types before undertaking more complex works, and indeed we can recognise in the lower animals the faint outlines of the higher.'[16] In other words, as well as having an intrinsic interest, the study of insects and 'lower' animals would reveal truths about 'higher' organisms. In and of itself, this was a decisive step towards a modern approach to biology in general and anatomy in particular.

At the beginning of 1669, Malpighi sent his manuscript to Oldenburg, stating

[9]M. Malpighi, 'Letter to Oldenburg (22.3.1668)', in A. R. Hall and M. B. Hall (note 5), pp. 271–272.

[10]H. Adelmann (note 5), p. 327.

[11]The suggestion that Oldenburg contact Malpighi came from Henry Sampson, microscopist and brother-in-law of the naturalist Nehemiah Grew, who had tried unsuccessfully to see Malpighi in 1667. Sampson may have heard of Malpighi's experiments. D. S. Lux and H. J. Cook, 'Closed circles or open networks?: communications at a distance during the scientific revolution', *History of Science*, 36 (1998), 179–211.

[12]Robert Hooke, *Micrographia, or Some Physiological Descriptions of Minute Bodies Made by Magnifying Glass With Observations and Enquiries Thereupon* (London, 1665).

[13]F. Redi, *Esperienze Intorno Alla Generazione Degl'insetti* (Florence, 1668).

[14]Marcelli Malpighi, *Opera Posthuma* (London, 1697), p. 77.

[15]H. Adelmann (note 5), I, 370. The problems associated with knowing exactly what apparatus Malpighi used are discussed in J. Bennet, 'Malpighi and the microscope', in *Marcello Malpighi, Anatomist and Physician*, ed. by M. Meli (Florence, 1997), pp. 63–72.

[16]Quoted in F. J. Cole, *A History of Comparative Anatomy* (London, 1949), p. 182.

that 'It is a pleasure to dedicate to the Royal Society the letter containing observations upon the silkworm made last summer as a manifest token of my duty towards it.'[17] The manuscript was received by Oldenburg at the beginning of March, was read before the Royal Society before the month was out,[18] and appeared in print on 15 July 1669 under the title *Dissertatio Epistolica De Bombyce.*[19] In less than 60,000 words and in forty-eight drawings, Malpighi's monograph described the anatomy of an insect in unprecedented detail. Apart from Plates I and IX, which respectively show a caterpillar and a dramatic figure of the male moth, none of the figures gives any sense of scale or of the place of the figured organ in the organism as a whole. As might be expected given the historic economic interest of the caterpillar — which is explained in some detail in the extensive introduction — Malpighi dealt mainly with the larval stage, and in particular dissected the silk gland, which he (re)discovered.[20] Figure 1 gives some indication of the scale of his advance over previous studies. Figure 1a shows a woodcut from the massive and occasionally wildly inaccurate encyclopaedia of insects assembled by Ulisse Aldrovandi (1522–1605), *De Animalibus Insectis Libri* (1602), clearly showing the dissection of the silk gland. Figure 1b shows a copper engraving of the silk gland from *De Bombyce*, revealing the impact of the microscope and of copper engraving as against woodcuts.

Overall, Malpighi provided a practical example of his comparative and reductionist experimental method: *De Bombyce* contains a series of comparative studies on locusts, butterflies, stag-beetles, crickets, slugs, bees and wasps, as well as experimental investigations. Thus Malpighi described the tracheae that punctuate the length of the insect body and showed that they were connected to the circulatory system in a manner that appeared to be analogous to the vertebrate respiratory system. To test whether the trachea were indeed involved in respiration, Malpighi first put caterpillars in water and noticed that small bubbles of air apparently escaped from the trachea. However, he realized that these bubbles could come from air trapped on the caterpillar's cuticle. He therefore went on to paint various portions of the caterpillar with oil, butter, lard, suet, and honey and observed the effects. If the trachea were covered with oil, 'the animal immediately had convulsions and died in the time it takes to say the Lord's Prayer'.[21] He noted that experiments with an air pump, carried out at the Royal Society, had shown that insects need air to survive, and wondered whether the continual movement of the insect abdomen was linked to some kind of breathing function. However, in the best Baconian spirit, he

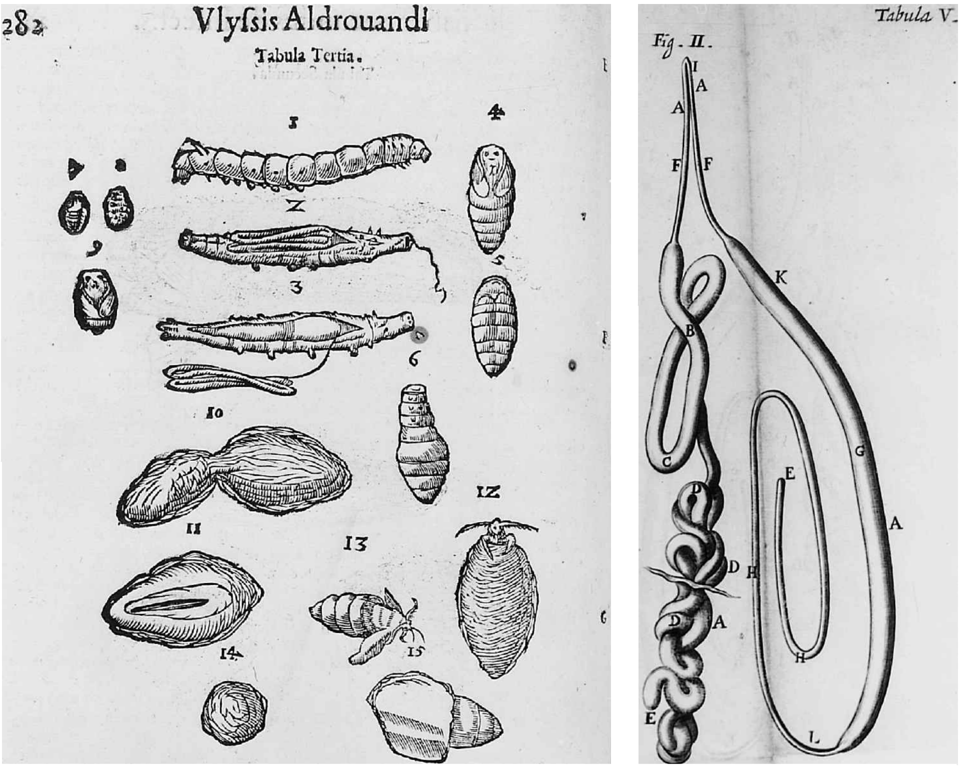
[17] M. Malpighi, 'Letter to Oldenburg (5.1.1668/9)', in *The Correspondence of Henry Oldenburg*, ed. by A. R. Hall and M. B. Hall (London, 1968), v, 323.

[18] H. Oldenburg, 'Letter to Malpighi (25.3.1669)', in A. R. Hall and M. B. Hall (note 17), p. 459.

[19] M. Malpighi, *Dissertatio Epistolica De Bombyce* (London, 1669). F. J. Cole (note 16, Figure 76) claimed that the manuscript 'does not quite agree with the published version'. In mid-1669 there was another manuscript of *De Bombyce* in existence, in the hands of G. D. Cassini, who at the time was Professor of Astronomy at Bologna (C. Huygens, 'Letter to Oldenburg, 16.6.1669', in *The Correspondence of Henry Oldenburg*, ed. by A. R. Hall and M. B. Hall (London, 1969), VI, 46). There is sadly no trace of any such manuscript in Cassini's papers at the Bibliothèque de l'Observatoire de Paris. *De Bombyce* sold for 7s. (H. Oldenburg, 'Letter to Paisen, 18.10.1669', in A. R. Hall and M. B. Hall, p. 286). The current asking price is around £4,400.

[20] F. J. Cole, a stickler for priority, points out that Libavius first described the silk gland in 1599 and Aldrovandi made a drawing of it in 1602 (F. J. Cole (note 16), p. 190 — see also Figure 1a). However, it should be noted that Malpighi made no claims for priority in this matter in *De Bombyce*, and that, although he referred to Aldrovandi's study, it was only in the more general context of previous studies of the silkworm.

[21] M. Malpighi (note 19), p. 30.



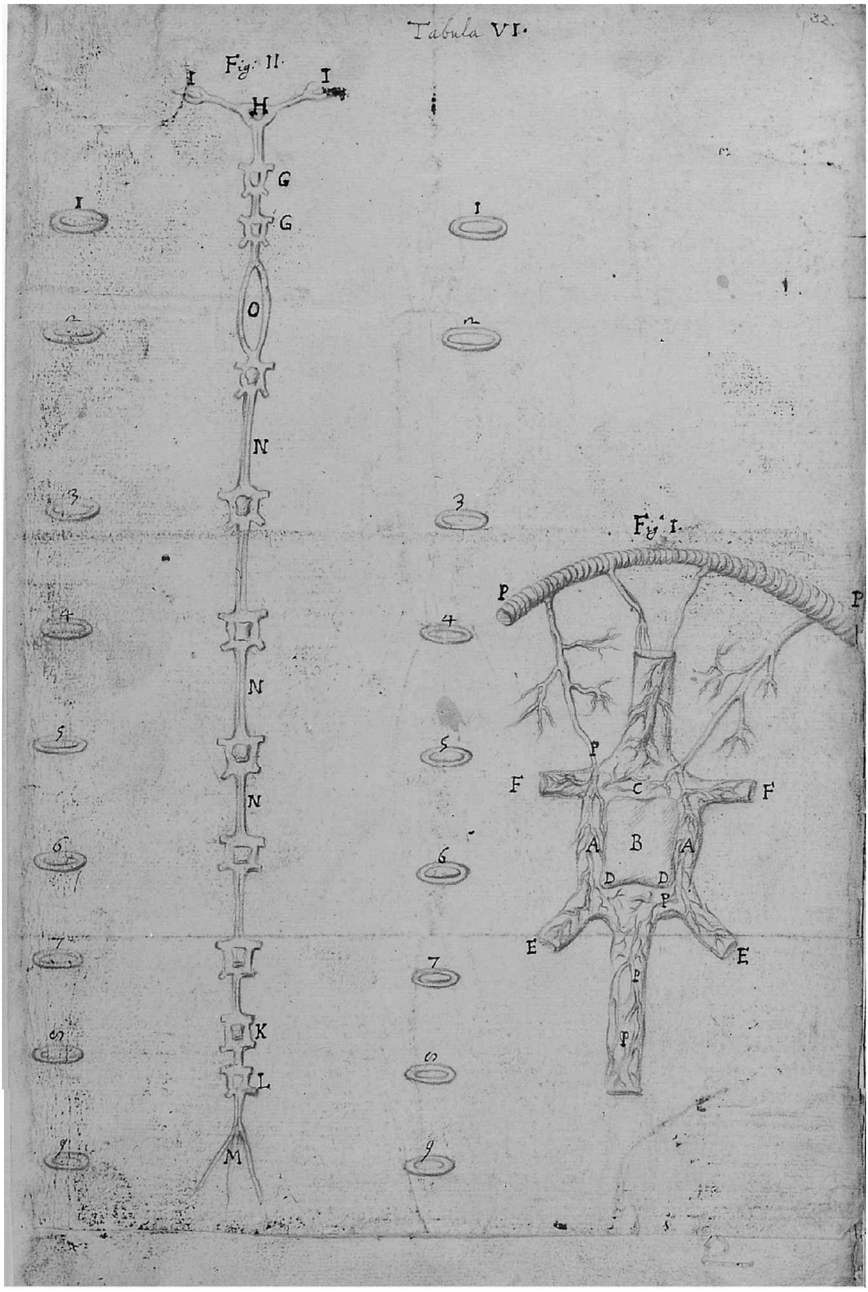
(*a*) (*b*)

Figure 1. (*a*) Woodcut showing the various stages in the life cycle of the silkworm, including two dissections showing the silk gland (labelled 2 and 3), from Ulisse Aldrovandi's encyclopaedia *De Animalibus Insectis Libri* (1602). © Bibliothèque Inter-Universitaire Medicale, Paris. Reproduced with permission. (*b*) Tabula V, Figure II from Malpighi's *Disertatio Epistolica De Bombyce* (1669) showing the silkworm caterpillar's silk gland. Malpighi has unravelled the right-hand gland to show its full length. © Bibliothèque centrale MNHN, Paris. Reproduced with permission.

concluded, 'I will not present you with my doubts and the pure imaginings of my mind: I wish to draw to your attention only facts that have been established by the witness of the senses.'[22]

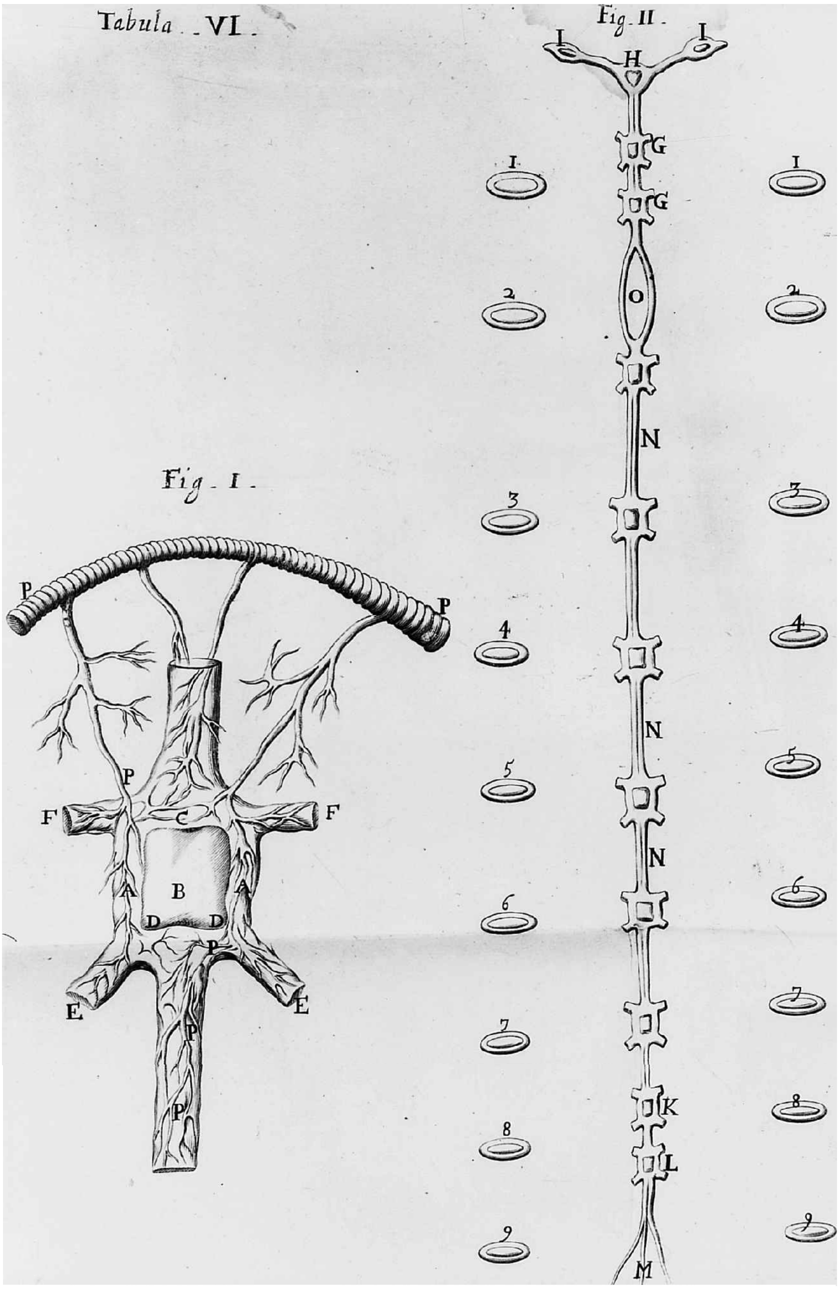
Although, unlike Aldrovandi, Malpighi was able to use sophisticated techniques of observation and reproduction, he still did not control the whole process of the graphic presentation of his findings to the public — all the more so given that the book was produced in London and he was far away in Bologna. Figure 2 shows both Malpighi's original drawing of the caterpillar's nervous system (Figure 2a) and the version made by the unnamed engraver employed by the Royal Society's printers, Martyn and Allestry (Figure 2b). The engraver has generally provided a faithful representation of Malpighi's original[23] (despite the reversal of the relative positions of the two Figures, the drawings have not been reversed in the printed version; although this is the case in some of the figures[24]). However, the proportions have

[22] M. Malpighi (note 19), p. 32.
[23] For F. J. Cole (note 16), p. 178, 'The engraved versions [...] are not worthy of the originals.'
[24] F. J. Cole (note 16), p. 190.



(*a*)

Figure 2. Tabula VI, Figure II from Malpighi's *De Bombyce* (1669) showing the organization of the 'spinal marrow', with the nine respiratory spiracles numbered on either side to indicate the position of the various ganglia with regard to the external form of the caterpillar. Note that Malpighi only shows eleven ganglia on this figure, whereas in fact there are thirteen (including the brain). F. J. Cole (note 16) describes this figure as 'crudely drawn' but 'reasonably accurate'. (*a*) Original sanguine drawing from the manuscript (MS 104, © Royal Society, London. By permission of the President and Council of the Royal Society), and (*b*) the printed version (© Bibliothèque centrale MNHN, Paris, reproduced with permission).



(*b*)

not been respected: the first ganglion (H) is relatively smaller in the engraving, and the distance between the first two ganglia (H and G) is greater on the printed version. More decisively, the first pair of spiracles (1) are figured by the engraver as being between what appear as the second and third ganglia (G and G), whereas the original shows them alongside the second of these ganglia. However, none of these mistakes was commented on at the time.

Oldenburg was justly proud of the work, describing it as 'a very curious and elaborat [*sic*] piece, accompanyed with 12. fine Iconisms in folio'.[25] Following the presentation of the book to the Royal Society, Oldenburg wrote to Malpighi that the Royal Society 'ordered me to return proper thanks to you in their name as soon as possible for this extraordinary gift of the Silkworm, and to inform you of their singular goodwill towards you and your studies.'[26]

The microscope was invented some time in the 1610s in Holland,[27] yet it had been over half a century before an Italian used the instrument to show the internal structure of an insect.[28] Malpighi's breakthrough can be attributed to a conjugation of factors. Firstly, as we have seen, he had long realized the power of reductionism and the importance of studying 'simple' organisms. This gave him a series of reasons to turn his attention to insects: not only did he expect to make discoveries that were worthwhile in their own right, he also thought they would provide more fundamental insights into biological processes and anatomy. In this view he was much influenced by his friend and colleague, Giovanni Borelli (1609–79), who had been taught by one of Galileo's students and sought to understand animal physiology in terms of physical laws. Second, Malpighi's combination of the microscope and careful dissecting skills had shown their worth in his discovery of the pulmonary capillaries and had further been reinforced by the impact of Hooke's *Micrographia* (1665). Third, at this time Italy had an unrivalled tradition in the use of the microscope, in particular to study insects: not only was the term 'microscopio' introduced by Johannes Faber in a letter to Prince Cesi, but the first known image made with the aid of a microscope (or at least a hand-lens) was a loose sheet, issued in 1625, with drawings by Francesco Stelluti (1577–1652) illustrating the honey-bee in a pastiche of the coat of arms of the recently elected Pope Urban VIII.[29] Subsequently, in 1644 Odierna made the first study of the fly's eye, in a short book illustrated with five small woodcuts,[30] while in 1646 Francesco Fontana used the microscope to study a number of subjects including the spider's eye.[31] *De Bombyce* followed this tradition, but also represented a radical break with it, because of its monographic nature, its length, and the quality of the work and the description presented therein.

Whatever the ultimate reasons for Malpighi being the first to carry out such a study, his book had an immediate, substantial and lasting effect:

It confirmed Malpighi's reputation as a major scientist. This was recognized

[25] H. Oldenburg, 'Letter to Downes (9.3.1668/9)', in A. R. Hall and M. B. Hall (note 17), p. 440.

[26] H. Oldenburg, 'Letter to Malpighi (25.3.1669)', in A. R. Hall and M. B. Hall (note 17), p. 459.

[27] See, for example, M. Fournier (note 3).

[28] Edward Ruestow has suggested a number of factors that may explain why Dutch scientists took so long to adopt the microscope, including the weight of Cartesianism, Calvinist negative attitudes to the contemplation of nature, and the traditions of naturalist miniature painting, which excelled in realistic representations of insects (E. G. Ruestow (note 2), pp. 61–80). For a discussion of Italian science after Galileo in the context of Italian economic decline in the seventeenth century, see Mario Biagioli, 'Scientific revolution, social bricolage, and etiquette', in *The Scientific Revolution in National Context*, ed. by R. Porter and M. Teich (Cambridge, 1992), pp. 11–54. For a discussion of an aesthetic explanation of Dutch microscopy, see Section 11.

[29] G. F. Bignami, 'The microscope's coat of arms', *Nature*, 405 (2000), 999.

[30] Giovanbattista Odierna, *L'Occio della Mosca* (Palermo, 1644).

[31] Francesco Fontana, *Novae Coelestium, Terrestriumque Rerum Observationes* (Naples, 1646). C. Wilson (note 3), p. 76, states that Fontana produced four pages of illustrations on insects using the microscope. There are no figures of microscopic studies or traces thereof in the copy of Fontana's book in the Bibliothèque Nationale de France. However, Fontana's verbal reports of his observations of insects do cover four pages, which would appear to explain the confusion.

by the Royal Society, who made him a Fellow on the day his book was read before them and sponsored the publication of all of his subsequent works.

It set the agenda for all future studies of invertebrate anatomy and development. Through its mixture of anatomical precision established via microscopic dissections, its in-depth monographic treatment of a single species, and its systematic use of the comparative and experimental approaches, Malpighi's study laid the basis for much of modern biology. In particular, the style of drawing, in which the insect was reduced to its parts, with no reference to its overall anatomy or its natural surroundings, helped to establish a new style of representation that eventually divided scientific illustration from natural history.

It had a major effect on the work of the second protagonist of this story, Jan Swammerdam. Right up until Swammerdam's death in 1680, Malpighi's work, in particular his dissection of the silkworm, was a continual reference for Swammerdam, to the extent that Malpighi was the only scientist outside of his student circle with whom he attempted a scientific dialogue.

3. The silkworm reveals its colours

In fact, what Oldenburg called Malpighi's 'extraordinary gift' was greater than has hitherto been suspected. The manuscript of *De Bombyce* is preserved at the Royal Society in London as part of two bound volumes containing all Malpighi's manuscripts published by the Royal Society.[32] The recto–verso *De Bombyce* manuscript, a small portion of which has been damaged, and other parts of which have been subject to the gnawing criticism of a bookworm, makes up the first thirty-eight pages of the second bound volume, corresponding to the printed version.[33] Malpighi's 1675 manuscript on plants, *Anatomes Plantarum*, begins on page 40. On page 39 there is an unmarked and unsigned illustration of the silkworm, which has never been reported, reproduced, or studied.[34]

This astonishingly vivid water-colour, about 25 cm long, shows a powerful side view of a silkworm caterpillar, painted on black paper roughly cut out and pasted on to a supporting sheet, and illuminated from the head end (see Figure 3). The fresh colours accurately show the ivory colour of the caterpillar, marked with black at the spiracles, and tinged with dark browny-red for the chitinous parts and some hairs. The painting was probably made with the use of at least a magnifying glass and perhaps a low-power microscope (a 'flea glass'): the hairs on the head and feet are clearly visible, and the degree of detail is greater than that shown, for example, on the painting of a silkworm caterpillar by Teodoro Ghisi[35] from the 1590s or on the 1662 engraving by Goedart.[36] The dim lighting reinforces the suggestion that

[32]Royal Society archives, MSS 103–04. The drawings in the two volumes are clearly all by the same hand. Malpighi declared in the preface to *Anatome Plantarum* (London, 1675) that he did the drawings published in that work, the originals of which are contained in MS 104.

[33]However, see note 23.

[34]The only detailed study of *De Bombyce* is that of Cole (note 16), pp. 183–197, in which he refers to the manuscript and reproduces some of the original drawings but makes no reference to the water-colour. Adelmann's major biographical study of Malpighi (note 5) makes no reference to the manuscript at all.

[35]Cynthia M. Pyle, 'Art as science: scientific illustration, 1490–1670 in drawing, woodcut and copper plate', *Endeavour*, 24 (2000), 69–75, Figure 6.

[36]Johannes Goedart, *Metamorphosis et Historia Naturalis Insectorum*, 3 vols (Middleburg, 1662–69), I, Plate XLII.

Figure 3. Untitled and unsigned water-colour of the silkworm caterpillar, found in the Royal Society archives at the end of the *De Bombyce* manuscript. MS 104, © Royal Society, London. By permission of the President and Council of the Royal Society.

the image was seen through a microscope, providing an astonishing glimpse into what the early anatomists actually saw. The technique, lighting, and inspiration of the illustration are clearly very different from previous paintings of insects, which tended to focus on well-lit subjects and used a much finer painting technique.[37]

This hitherto unknown figure raises a number of intriguing questions. First, what is its provenance? There is no reference in the surviving correspondence by Oldenburg or Malpighi to this painting. The Royal Society archives have no independent trace of it either; the volume of Malpighi's manuscripts was bound and the pages numbered in the 1930s. Beyond that, nothing is known. However, everything suggests that it is contemporary with the rest of the *De Bombyce* manuscript. The paper on to which the water-colour has been pasted is of the same size and appears to be of the same facture as the rest of the manuscript. The emphasis on the rotundity of the caterpillar, the broad brush strokes, and in particular the illustration of the creases around the second and third abdominal segments, are highly reminiscent of Malpighi's line drawing of a silkworm which appears in the first plate of *De Bombyce*. The most parsimonious explanation is that the water-colour either is by Malpighi or was commissioned by him.[38] Whoever the author was, they were clearly a skilled artist and had a profound understanding of the silkworm's external anatomy: the illustration gives us a unique impression of the silkworm and of the vision of the early microscopists. No representation quite as powerful exists in the work of any other pioneer of microscopy.

Second, assuming that the illustration did indeed form part of the manuscript, why did Malpighi choose to send the Royal Society an image that could not be fully reproduced? If he had wanted it to be engraved, the simplest approach would have been to eradicate the colour information by producing an image in tones of grey ('*grisaille*'). Despite the powerful impression it conveys and its undoubted scientific value — it is far more accurate in both its detail and the impression it conveys than any previous illustration of a caterpillar — it does not in fact provide any more precise anatomical information than is contained in *De Bombyce*. However, given that the changing colour of the caterpillar through its various moults is described in some detail in *De Bombyce*, and that subtle and economic colour reproduction was technically impossible (the only option at the time was to hand-colour copper engravings), this illustration may have been the only way of graphically and tellingly demonstrating what the silkworm looked like under the lens, even though it could only convey that information to those who were able to see the original. This final point raises a thorny question, which is neither fatuous nor entirely rhetorical: is it art?

4. Swammerdam and the silkworm

By 1669, thirty-two-year-old Jan Swammerdam had already gained an international reputation for his works in anatomy and physiology.[39] His doctoral disserta-

[37]See, for example, Jacques de Gheyn's magnificent water-colours of a variety of insects (including two caterpillars), executed between 1600 and 1604, held at the Fondation Custodia, Institut Néerlandais, Paris, under the catalogue number PLS 20-41.

[38]For Joanna Corden, archivist at the Royal Society, 'the illustration is very similar to the other drawings in MS 104, even though the colouring is not; [...] in terms of page size, format, kind, and paste used it appears to be part of the same collection'. J. Corden (personal communication, 2001).

[39]For a brief account of Swammerdam's life and work, see M. Cobb, 'Reading and writing The Book of Nature: Jan Swammerdam (1637–1680)', *Endeavour*, 24 (2000), 122–29. For a biography see A. Schierbeek, *Jan Swammerdam 1637–1680: His Life and Works* (Amsterdam, 1967).

tion on the physiology of respiration, *De Respiratione* (1667), which had attracted the attention of Oldenburg and others (including Malpighi)[40] and was reprinted twice in his lifetime, showed that Swammerdam had a keen experimental mind, as he reported a series of (gruesome) experiments to confirm, among many other things, his mistaken conviction that air enters the lungs because expansion of the chest compresses the surrounding air. Swammerdam was also renowned for his interest in insects; in particular, a number of contemporary sources from the second half of the 1660s recount that he publicly dissected out the soft and fragile forms of some of the organs of the adult butterfly from within the body of the late caterpillar, shortly before pupation.[41] (This discovery and his later description of it were at least partly responsible for his posthumous reputation as a founder of 'preformationism'.[42]) By September 1667, Henry Oldenburg had heard that a 'Dutch man' (presumably Swammerdam) was working on a book on insects.[43]

Swammerdam's book, eventually published in Dutch in late 1669 under the Latin title *Historia Insectorum Generalis*,[44] is an audacious attempt to classify 'insects' (including spiders, snails, and scorpions) according to their modes of metamorphosis. It contains thirteen beautifully drawn plates, mostly showing naturalistic views of invertebrates that would have required nothing more than a low-power microscope or 'flea-glass', but no examples of dissection. At this stage, Swammerdam's aim was to demonstrate that there was a direct continuity between egg, larva, and adult insect, and that there was no evidence for 'metamorphosis' in the sense of a transmutation of one individual into another, or for spontaneous generation.

The publication of *De Bombyce* occurred while Swammerdam's book was being printed. However, he was able to insert a large quotation from Malpighi's book describing the metamorphosis of the silkworm and including the clear statement that some rudimentary structures of the adult butterfly (for example the wings) can be found in the late caterpillar, prefaced by the following words:

> Whilst the preceding sheets were at the press, the incomparable anatomical observations of Dr. Marcellus Malpighius, professor of physic and philosophy, in Bologna, on the Silk-Worm, and its Butterfly, which the Royal Society of London, instituted to promote natural knowledge, caused to be published this year, 1669, were kindly sent to me by the noble Thévenot, whose merit and zeal to promote natural knowledge, are sufficiently known to all who

[40] A. R. Hall and M. B. Hall (note 5), pp. 56, 57, 285 and 239. Quoted by A. Schierbeek (note 39), p. 71. Some time between 1667 and early 1673, Malpighi acquired a copy of Swammerdam's book ('Letter from d'Andrea to Redi, (28.1.1673)', in *Marcello Malpighi, Anatomist and Physician*, ed. by M. Meli (Florence, 1997), p. 305).

[41] J. Nordström, 'Swammerdamiana. Excerpts from the travel journal of Olaus Borrichius and two letters from Swammerdam to Thévenot', *Lychnos*, 16 (1954–55), 21–65. 'Lettre anonyme, October 24 1669' in Harcourt Brown, *Scientific Organizations in Seventeenth Century France (1620–1680)* (Baltimore, 1934), 280–281.

[42] According to F. J. Cole, Swammerdam's view of insect metamorphosis 'led him to adopt, if not to promulgate, the Preformation Doctrine, the long and evil reign of which lies so heavily on his reputation' (note 16), p. 304. For a more balanced view, see Jacques Roger, *Les Sciences de la Vie dans la Pensée Française au XVIIIe Siècle* (Paris, 1963).

[43] H. Oldenburg, 'Letter to Boyle (17.9.1667)', in *The Correspondence of Henry Oldenburg*, ed. by A. R. Hall and M. B. Hall (London, 1966), III, 476.

[44] J. Swammerdam, *Historia Insectorum Generalis, ofte Algemeene Verhandeling der Bloedeloose Dierkens* (Utrecht, 1669). 'A general history of insects, or, a general history of bloodless animalcules'. 'Bloodless' refers to the Aristotelian belief that insects had no blood or internal organs to speak of.

> happened to be at Paris, and present at the weekly disputations instituted by him.[45]

Swammerdam went on to praise Malpighi's 'extraordinary accuracy' and to state that 'after that exact observer, Andrew Libavius, he is the only person who excludes the fancied metamorphosis from the natural course of the changes, which the Silk-Worms undergo'. For Swammerdam in 1669, the fundamental point about Malpighi's work was his statement that 'the new kind of life in the Aurelia [pupa] is only a mask or veil of the Butterfly, which is already perfect within; intended that it should not be struck or destroyed by external injuries, but might grow strong, and ripen, as a foetus in the womb.'[46] This coincided completely with his dissections of butterfly pupae and his views of the continuity of life between the insect's various stages.

In November 1669, two correspondents told Oldenburg of the publication of the *Historia Insectorum Generalis*,[47] but it was only in July 1670 that he informed Malpighi of Swammerdam's praise:

> There has lately appeared in the Dutch language the *Historia insectorum generalis*, *pars prima*[48] of Dr. Swammerdam, in which he makes a laudatory mention of your De bombyce and admits that you are the sole author who has given a solid account of the true manner of the silkworm's metamorphosis. We hope that the author himself will take care to have this offspring of his exposed to the philosophers of all peoples as soon as possible, in the language of learning.[49]

Four months later, Malpighi replied to Oldenburg:

> I am also very anxious to have the famous Swammerdam's book on insects, whose very pretty illustrations I have seen, and in the meantime I am much indebted to so great a man for his flattering reference to myself, which you mention.[50]

Like Swammerdam, the Royal Society understandably felt that the link between the findings on insect metamorphosis in *De Bombyce* and those in *Historia Insectorum Generalis* was of major importance, because two separate and well-constructed

[45]This section was subsequently inserted, word for word, into Swammerdam's posthumous work *Bybel der Natuur*, either by Swammerdam himself or by his editor Boerhaave. This translation is from J. Swammerdam, *The Book of Nature*, 2 vols (London, 1758), II, 2. Melchisedec Thévenot — French diplomat, bibliophile and patron of the sciences — was Swammerdam's friend and patron. On his death, Thévenot's massive library (the catalogue — *Bibliotheca Thevenotiana* (Paris, 1694) — runs to 249 closely printed pages) did not contain Malpighi's *De Bombyce*. It seems probable that Thévenot sent his own copy to Swammerdam.

[46]M. Malpighi (note 19), p. 61. This translation is taken from J. Swammerdam (note 45), II, 3.

[47]Paisen, 'Letter to Oldenburg (27.11.1669)': 'I am told from Holland that Swammerdam (who formerly published a book of respiration) has now published one on insects. I have not yet seen that book', in A. R. Hall and M. B. Hall (note 5), p. 341. M. Vogel, 'Letter to Oldenburg (27.11.1669)': 'Thevenot recently informed me that he is sending me Swammerdam's book on insects', in A. R. Hall and M. B. Hall (note 5), p. 347.

[48]Oldenburg's description of the book as '*pars prima*' ('first part') is presumably based on a mistaken reading. The book does indeed contain two parts, but they are bound together.

[49]H. Oldenburg, 'Letter to Malpighi (15.7.1670)', in *The Correspondence of Henry Oldenburg*, ed. by A. R. Hall and M. B. Hall (London, 1970), VII, 72. A Latin translation was published in 1685.

[50]M. Malpighi, 'Letter to Oldenburg (21.11.1670)', in A. R. Hall and M. B. Hall (note 49), p. 244. Malpighi's biographer, Howard Adelmann, makes a mystery of this letter by stating 'I am unable to explain how Malpighi came to see these figures of Swammerdam's before the book came into his hands.' (H. Adelmann (note 5), p. 715). The explanation seems quite simple: he had seen someone else's copy.

studies arrived at the same radical explanation of one of the major enigmas of natural history. An unsigned and untitled 'account' of Swammerdam's book appeared in the *Philosophical Transactions* in October 1670. The article consists of a summary of 'This Curious and Philosophical Book, written in the *Belgick* tongue' in which the author concludes by stating that Swammerdam argues 'that the doctrine of Seigneur *Malpighi*, in his Dissertation de *Bombyce* (dedicated to the *R. Society*,) concerning the change of Butterflyes, is true.'[51]

5. Swammerdam replicates Malpighi's work

Although Swammerdam's immediate reaction was to embrace Malpighi's findings as support for his campaign against 'transformation', he also had another, more important, and lasting response. He was inspired.[52] A comparison of his investigations contained in *Historia Insectorum Generalis* (1669) and those that appeared in his next major published work, on the mayfly (*Ephemeri Vita*, 1675), shows that a series of fundamental changes had taken place in Swammerdam's science. Most importantly, he began to study the internal structures of insects using microscopy, dissection, and careful experimentation. Also, like Malpighi, he presented his vision to the world via some stunning drawings, in which the component anatomical parts are treated as separate, isolated, and often utterly strange objects, without reference to size or function. In other words, Swammerdam followed in Malpighi's footsteps.

It is not clear why Swammerdam apparently had to wait for Malpighi's initiative before beginning to use the microscope to study insect dissection. Swammerdam was carrying out relatively crude dissections of large insects in the second half of the 1660s[53](for example his study of the ovaries in the 'king' bee with van Horne in *c.*1667[54]), and at the same time he was using at least a 'flea-glass' to observe the external forms of insects. However, prior to 1669 he never put the two skills together; indeed, in *Historia Insectorum Generalis* he argued that the smallness of the internal organs of 'animalcules' made it impossible to dissect them.[55] Malpighi clearly proved him wrong. The next records of Swammerdam's work, in 1671, show that his immediate reaction was to try to repeat (replicate) Malpighi's dissections. Swammerdam subsequently gave two explanations for this. First, as a general principle, he would not take anyone else's word for it:

> In questions of anatomy, I speak like I think, I do not believe anybody — I barely believe my own eyes — and there is nobody with whom I will blindly agree in matters of experiments, in which I think I have a certain ability.[56]

There are four points that need to be noted with regard to this statement. To start with, strictly speaking it is not true. Throughout his life Swammerdam was, of

[51] *Philosophical Transactions*, 6 (1670), 2078–80.

[52] E. G. Ruestow (note 2, p. 124) provides some more precise psychological speculations about Swammerdam's response: 'How unnerving it probably was, then, when Malpighi's De bombyce suddenly appeared, displaying skills in Swammerdam's chosen field of which Swammerdam had scarcely dreamed! It was presumably a threatened as well as an acutely competitive Swammerdam who set out with such determination to equal and surpass Malpighi's remarkable achievement.'

[53] Swammerdam's earliest reference to insect dissection is in a letter to Thévenot of 15 October 1665 in G. A. Lindeboom, *The Letters of Jan Swammerdam to Melchisedec Thévenot* (Amsterdam, 1975), pp. 42–44.

[54] E. G. Ruestow (note 2), p. 109.

[55] J. Swammerdam (note 44), I, 1.

[56] J. Swammerdam, *Miraculum Naturae sive Uteri Muliebris Fabrica* (Leiden, 1679), p. 16.

course, obliged to take the word of other natural historians — to do otherwise would be to reduce science to a solipsistic exercise bounded by the activity of a single individual. However, behind the rhetoric lurks a second, more important consideration: Malpighi's findings were clearly so profoundly novel that Swammerdam felt obliged to repeat them in order fully to acquire the knowledge and skills they represented, as well as to verify them in their unprecedented detail. This is the germ of the modern reasoning behind the concept of replication.

This last point leads on to the second reason given by Swammerdam for trying to repeat Malpighi's results. Swammerdam later stated that he did not know how Malpighi had carried out his dissections, and so he had to develop his own methods:

> We need to carry out common studies and to communicate the method; however, despite this, something will always be missing: something will always be able to be added. When I began to carry out Malpighi's experiment, I did not know what method he used, and this seemed to me to be deplorable. At some points I admired the skill and honesty of this great man. But I subsequently managed by chance to find another method and overcome all these difficulties.[57]

Swammerdam's remarks are understandable: although *De Bombyce* contained details about the effects of different kinds of mulberry bush (or even lettuce) on silk quality, it did not contain a single word as to how the dissections were carried out — using what kind of microscope, what techniques for preparing the material, and what instruments for carrying out the dissection. In the only section that related to technique, Malpighi merely stated that his muscle dissections had extremely variable results and that 'I will describe about this matter that which I have seen which is the least doubtful and on dissecting a large number [of caterpillars]'.[58]

When Swammerdam carried out his dissections of the silkworm, his findings did not entirely agree with Malpighi's. In a letter to Thévenot, written in 1671, Swammerdam stated:

> I experienced something about the silkworms that Malpighi has not observed. I do not know whether I shall write to himself, or whether I shall have it printed; it concerns the heart, the medulla spinalis, and the orifices of the bronchi.[59]

His initial decision was apparently to approach Malpighi, through the good offices of their mutual friend, Steno. On 24 November 1671, Steno wrote in Italian to Malpighi:

> Mister Swammerdam asks me to greet you with all affection. He has tried to carry out the experiments on the silkworm and, having found that most were as you described them, found some differences in others. He asks me if you would prefer him to print them or if he should send them to you because he dearly wishes you to know his esteem for you.[60]

Less than a month later, news of Swammerdam's drawings was circulating in the European scientific community. On 10 December 1671 Nicolaes Witsen wrote to

[57] J. Swammerdam (note 56), p. 18.
[58] M. Malpighi (note 19), p. 23.
[59] This letter cannot be dated more precisely. G. A. Lindeboom (note 53), p. 64.
[60] M. Malpighi (note 14), p. 59.

Oldenburg, announcing that 'I shall soon send you the various anatomical sketches made by Jan Swammerdam, of the silkworm, the reproductive system of the bee, etc.'[61] There is no trace of these sketches ever having been sent.

Swammerdam's attempts at replication show us two things. Firstly, it is significant that, once he realized there was a discrepancy between his findings and those contained in *De Bombyce*, his reaction was to contact Malpighi. This unique event — there are no records of Swammerdam proposing such an exchange with any other of his contemporaries — must indicate that Swammerdam had a high degree of scientific and personal confidence in Malpighi. It also implies that he did not immediately think of making a reputation by publicly demonstrating Malpighi's errors. Second, there is no indication that Swammerdam attempted to replicate systematically Malpighi's experimental findings. In other words, his inspiration was primarily anatomical, although both his previous and subsequent work demonstrated his keen interest in experimentation.

6. Swammerdam publicly criticizes Malpighi

Swammerdam's findings were published in 1672, in his study of the human uterus, *Miraculum Naturae sive Uteri Muliebris Fabrica.* Completed on 15 March 1672 and published in Amsterdam on 1 May 1672, this somewhat polemical work, dedicated to the Royal Society, gave Swammerdam a disputatious reputation that has followed him down the centuries. The central thrust of the book was Swammerdam's claim that Van Horne, Steno, and himself had priority over his one-time student friend de Graaf in the discovery of 'eggs' (in fact follicles) in the human ovary, and Swammerdam called on the Royal Society to arbitrate. This complex dispute, which according to van Leeuwenhoek led to de Graaf's early demise the following year,[62] merits a separate study in the context of the mechanisms for settling priority disputes in early modern science.[63] For our present purposes, it will suffice to note that Swammerdam also used his small book to outline his differences with Malpighi.

Miraculum Naturae is divided into three sections: the anatomy and physiology of the male and female reproductive organs including the structure of the veins and arteries, the methods Swammerdam used to preserve his specimens, and a description of the experiments he carried out with Van Horne. In the first part, Swammerdam describes the uterus and the structure of the erectile material in the human penis, drawing parallels with the structure of the lungs as described by Malpighi, and describing for the first time how erection takes place. It also describes the human testes and ejaculatory duct, and it is at this point that Swammerdam, quite naturally, inserted a discussion of the silkworm and his attempts to replicate Malpighi's work.

Swammerdam prefaced his disagreement with his general statement on not taking other people's word for it, which, he argued, even extended to Malpighi, 'someone who is very careful and whom I consider to have made a very great contribution to the study of anatomy in our epoch, by his careful and detailed work, but above all

[61] N. Witsen, 'Letter to Oldenburg (10.12.1671)', in *The Correspondence of Henry Oldenburg*, ed. by A. R. Hall and M. B. Hall (London, 1971), VIII, 396.

[62] It seems more likely that de Graaf died of the plague. See A. Schierbeek (note 39), p. 83.

[63] The Royal Society did not accept Swammerdam's claim and today the ovarian follicles are known as 'Graafian follicles'. For a detailed and even-handed discussion of the question, see *The Correspondence of Henry Oldenburg*, ed. by A. R. Hall and M. B. Hall (London, 1973), IX, 586–88. For the context to this debate, see J. Roger (note 42).

by his honesty and his integrity, which can be seen in the things he studies and of which the incomparable book *De Bombyce* provides a remarkable proof.'[64]

In print, Swammerdam went further than in his letter to Malpighi, adding a disagreement over the male genitalia and expressing his differences in terms that were in stark contrast to the flattery that preceded them:

> not only have I observed errors here and there in the Figures, but I have discovered in this work some even more serious things. The Figures made by this great man are mistaken especially with regard to the spermatic system and the spinal marrow. As far as the former is concerned, not only does he place the testicles in a strange place, but it even seems that the figure was conceived by his mind. I think the reason for this error is as follows: being unable to extract these very delicate parts from the small body [of the caterpillar] whilst keeping the natural links intact, he removed the parts and displayed them so he could study them better.[65]

Having effectively accused Malpighi of making up one of his drawings, Swammerdam explained what he thought was the correct organization of the male genital tract, in particular the absence of any communication of the sperm 'bags' and the vas deferens (see also Figure 6). He then explained his disagreement over the organization of the nervous system:

> Something else that is mistaken in these figures is as follows: he has drawn a spinal marrow, which in the silkworm is by nature connected to the brain, separately from and without the brain. The reason for this mistake is that, as he says himself, he did not find a brain in the silkworm.[66]

Swammerdam further disputed Malpighi's suggestion that the caterpillar has several hearts and he had a different interpretation of the shape and structure of the tracheal openings. Given his subsequent emphasis on drawings in order to demonstrate his insect anatomical discoveries, it is striking that Swammerdam provides no figures to accompany his claims in his 1672 work. His need to publish quickly, in response to de Graaf, may explain this.

During his lifetime, Malpighi made no public reply to Swammerdam's criticisms. It was only with the publication of his *Opera Posthuma* in 1697 that his opinion became known, while the full detail of Swammerdam's findings only came to light with the publication of *The Book of Nature* in 1737 (see Section 9). However, as subsequent events made clear, the two men were aware of each others' work and continued to consider each other as a fundamental reference with regard to their research.

7. Oldenburg tries to play the middle-man

Henry Oldenburg played an important role in the lives of both Malpighi and Swammerdam, demonstrating the attitude that he thought the Royal Society should

[64] J. Swammerdam (note 56), p. 16.

[65] J. Swammerdam (note 56), pp. 16–17.

[66] J. Swammerdam (note 56), pp. 16. Swammerdam was not the only contemporary reader to have understood Malpighi this way. The famous anatomist Thomas Willis summarized Malpighi's work as follows: 'As to the head, our most diligent investigator observes that the insect has no brain in its skull'. T. Willis, *De Anima Brutorum* (London, 1672), p. 36.

have towards eminent scientists overseas.[67] This is particularly clear in the case of Malpighi: from 1669 onwards, he ensured that the Royal Society published Malpighi's works and thus that the spread of Malpighi's fame coincided with that of the Royal Society. His relations with Swammerdam were less decisive, but important nevertheless, as throughout the 1670s he followed and encouraged Swammerdam's research into both human and insect anatomy. His encouragement of Swammerdam when the latter emerged from his encounter with Antoinette Bourignon's sect after 1676 understandably touched Swammerdam, who wrote on 31 August 1677:

> You do well, my good friend Oldenburg, and act the part of a friend properly when by repeated letters you recall me to the contemplation of nature, thinking me languid and unmindful of my former concerns.[68]

Oldenburg's main correspondence with Swammerdam related to the research that was summarized in *Miraculum Naturae*. However, Oldenburg clearly wanted to encourage some kind of collaboration — or emulation — between Swammerdam and Malpighi. Not only did he keep Malpighi informed about Swammerdam's comments about *De Bombyce* in *Historia Insectorum Generalis* (see Section 3), in 1672 he wrote a rather chatty letter to Swammerdam describing Grew and Malpighi's work on plant anatomy, and Malpighi's latest findings on the chick embryo and the way in which they had been supported by Croone.[69] Oldenburg, well aware of the apparent conjuncture of interest in early development shown by the two men, closed his letter with an open encouragement to Swammerdam to enter the fray:

> Thence others, if I mistake not, will take on further to exercise their own industry and intelligence, in order to investigate and elucidate the true nature of reproduction that has hitherto remained concealed. You yourself, learned Sir, will not scruple to add your contribution to further this end, and so increase our knowledge of nature.[70]

Some weeks later, Oldenburg wrote to Swammerdam to thank him for sending the copy of *Miraculum Naturae*, and again used an intimacy that can be felt across the centuries:

> I very willingly presented your handsome gift, famous Sir, to the Royal Society at its ordinary meeting. It thinks the more highly and warmly of you because you so eagerly maintain a scientific correspondence and indeed do not hesitate to furnish us with a very welcome present, in this very difficult period when the weight of war lies heavily on both our peoples and tends to bring about a

[67]For discussions of this aspect of Oldenburg's work, see M. B. Hall, 'Oldenburg and the art of scientific communication', *British Journal for the History of Science*, 2 (1965), 277–90, and M. Hunter, 'Promoting the new science: Henry Oldenburg and the early Royal Society', *History of Science*, 26 (1988), 165–181.

[68]J. Swammerdam, 'Letter to Oldenburg (31.8.1677)', in *The Correspondence of Henry Oldenburg*, ed. by A. R. Hall and M. B. Hall (London, 1986), XIII, 343–44. Oldenburg's 'repeated letters' from this period have unfortunately been lost.

[69]H. Oldenburg, 'Letter to Swammerdam (24.4.1672)', in A. R. Hall and M. B. Hall (note 63), pp. 40–42. Oldenburg apparently wrote a similar letter to de Graaf on the same day, although only a summary survives: A. R. Hall and M. B. Hall (note 63), p. 40. Croone's support for Malpighi's suggestion that embryonic structures could be detected in the unincubated embryo was to prove decisive in the development of preformationism. See J. Roger (note 42).

[70]H. Oldenburg (note 69). Swammerdam and Steno had already carried out research on the chicken embryo in 1665. It was published by Thomas Bartholin in 1675.

> baleful separation between the minds of Englishmen and Dutchmen. It is indeed proper that honest and true philosophers should, while the princes of the world contend fiercely over questions of mine and thine, persist in the peaceful search into nature's secrets and in advancing with utmost zeal the limits of truth and knowledge.[71]

Both Oldenburg and Swammerdam referred to Malpighi on a number of occasions. In February 1673 Oldenburg wrote to Swammerdam and again encouraged him to continue his work:

> Go on with your assiduous investigation of nature and her secrets, learned Sir, so as to acquire for yourself eternal distinction as a student of virtue and science. Certainly there are philosophers active in this way, among whom the merits of the famous Malpighi earn him first place.[72]

In reply, in March 1673, Swammerdam proclaimed his desire to 'follow in the footsteps of the very famous and delightful Malpighi' whom he described as 'very experienced' and 'most delightful'.[73]

However, despite Oldenburg's keen sense that it would be possible to inspire Swammerdam by invoking Malpighi, or even to encourage him to emulate Malpighi's work, in the period 1673–75 Swammerdam gradually began to lose his mental struggle between his desire to carry out scientific research and his mystical Christian leanings. The nadir of this intellectual decline occurred in 1675, when he joined the bizarre French mystic Antoinette Bourignon on her island off the Danish coast.[74] However, even at this point, when Swammerdam was at his most distant from science, Malpighi and their studies on the silkworm were not far from his mind.

8. The pivotal moment: Swammerdam sends his drawings to Malpighi

The most dramatic expression of Swammerdam's decision to abandon science in order to follow Bourignon was his destruction of his manuscript on the silkworm. He did so as he was about to publish what he clearly thought was his scientific swan-song, his study of the mayfly *Ephemeri Vita*, which was weighed down with prayers and religious poems.[75] Destroying his work on the silkworm was presumably intended as a symbolic gesture to demonstrate his determination to abandon what Bourignon had told him were 'Satan's games'.[76] However, just as *Ephemeri Vita* contains a number of passages that clearly contradict Swammerdam's avowed disdain for his scientific work,[77] so too his gesture with respect to his silkworm study was profoundly ambiguous. For Swammerdam did not destroy all his work: through

[71] H. Oldenburg, 'Letter to Swammerdam (13.6.1672)', in A. R. Hall and M. B. Hall (note 63), pp. 104–06.

[72] H. Oldenburg, 'Letter to Swammerdam (10.2.1673)', in A. R. Hall and M. B. Hall (note 63), pp. 460–462.

[73] J. Swammerdam (note 68).

[74] For an account of Bourignon's life and theology, see Marthe van der Does, *Antoinette Bourignon: Sa Vie (1616–1680) — Son Œuvre* (Amsterdam, 1974).

[75] Henri Justel complained: 'This book is full of metaphysical and theological speculations, which annoy those whose only aim is to know nature.' Justel, 'Letter to Oldenburg (12.8.1675)', in *The Correspondence of Henry Oldenburg*, ed. by A. R. Hall and M. B. Hall (London, 1977), XI, 454.

[76] G. A. Lindeboom, 'Antoinette Bourignon's first letter to Jan Swammerdam. A contribution to his biography', *Janus*, 61 (1974), 183–99.

[77] A. Schierbeek (note 39), p. 47.

Steno, Swammerdam sent twenty-four drawings to Malpighi. Steno sent them to Malpighi on 18 July 1675, with a note in Italian which read:

> Mister Swammerdam sent me the attached figures, to be sent to you if you would be so kind as to accept them, at a time when he is abandoning his studies of nature. He began a study of the same subject, but he destroyed the rest, keeping only the figures. He is looking for God, but not in the Church of God. Pray for him and ask those of your friends who are true servants of God to pray for him. I take this opportunity to remind you that I remain your true friend and I pray you will realise his esteem for you.[78]

In all its respects, this gesture shows Malpighi's importance for Swammerdam. At a moment when Swammerdam was supposedly leaving the scientific world once and for all, he sent some precious drawings to his Italian master and, perhaps, competitor. As he confessed in the pages of *Ephemeri Vita*, 'I have striven night and day to surpass others and to raise myself above them with ingenious inventions and subtle techniques'.[79] Indeed, the gesture was clearly not neutral: Swammerdam was presumably trying to demonstrate to Malpighi which of them was correct in their (minor) dispute, providing the visual evidence that was lacking in his original presentation in *Miraculum Naturae*. Finally, it is striking that, once again, Swammerdam did not contact Malpighi directly — indeed, there is no evidence that, despite their obvious fascination for each other, the two men ever corresponded directly. This example of late seventeenth-century European etiquette could imply that Swammerdam did not consider himself to be Malpighi's equal, despite his conviction that he had made a better dissection of the silkworm.[80]

The fate of the drawings is obscure. Although they were sent to Malpighi in 1675 (Malpighi died in 1695), less than 100 years later they turned up in the hands of one Doctor Donelli, who offered to sell a job lot of ninety pages of Malpighi's manuscripts, including Swammerdam's drawings, to the Scientific Institute of Bologna for the sum of 20 ducats.[81] Today Swammerdam's drawings can be found in the Bologna University Library under the reference Ms 936, mounted on a sheet of paper 26 cm × 40 cm.[82]

[78]M. Malpighi, (note 14), p. 59.

[79]Cited and translated by E. G. Ruestow (note 2), p. 119.

[80]For a discussion of the importance of social networks during this period, see D. S. Lux and H. J. Cook (note 11).

[81]In 1766, Francesco Bibiena wrote to Montefani, librarian of the Institute, outlining Donelli's proposal, saying that he thought the sum was quite reasonable and that 'If I was not as poor as I am I would not hesitate to buy them at this price.' C. Frati, *Bibliografia Malpighiana* (Milan 1897), p. 8.

[82]Although Steno's letter accompanying the drawings was published and widely circulated in Malpighi's *Opera Posthuma*, it was to be nearly 300 years before the fact that Swammerdam had sent these documents to Malpighi became known to students of Swammerdam's work. Boerhaave, in his 1737 biographical introduction to *The Book of Nature* (Swammerdam, note 45), made no mention of the fact, neither did Schierbeek (note 39), author of the only full modern account of Swammerdam's life and work, nor did F. J. Cole (note 16). None of the nineteenth-century accounts of Swammerdam's life (e.g. James Duncan, 'Memoire of Swammerdam' in *The Naturalist's Library. Introduction to Entomology*, ed. by W. Jardine (Edinburgh, 1840); P. Harting, 'Johannes Swammerdam. Een Levensschets', *Album der Natuur* (1876), 1–28) made any reference to the drawings, although by the end of that century they were on display in the Manuscript Room of the Bologna University Library, where they remained until 1972 (L. Miani, personal communication, 2000). It appears that the story was first recounted by C. Frati (note 81), and, although it appeared in L. C. Miall's book *The Early Naturalists: Their Lives and Work* (London, 1912), p. 179, it was only in 1975 that it definitively entered the literature on Swammerdam (Lindeboom, note 53). It is now routinely included in accounts of Swammerdam's life and work. See for example M. Fournier (note 3), E. G. Ruestow (note 2), or M. Cobb (note 39).

The only published account of Swammerdam's drawings of the silkworm consists of a summary description of around 200 words, together with a poor black and white reproduction.[83] This is the first time they have been published in colour (Figure 4 — for a key see Figure 5), interpreted, or analysed. Ten of the figures have been mounted by inserting them into diagonal corner cuts; the others have been fixed to the back of the card. There is a large stain covering about 40% of the surface area, all the paper shows signs of light fading (as shown by the lighter appearance of Figure 4t), and one set of figures (Figure 4x) shows severe foxing, but in general the drawings are clear. All but one of the figures uses colour, nineteen of them being full-colour illustrations. Five of them (figures 4c, d, e, s, w) were done on dark brown paper. They are accompanied by a short Latin text in Malpighi's hand which reads 'Drawings of Bombyx done by Master Swammerdam, which he gave to me because he was abandoning his studies of anatomy, and which were transmitted by Master Stenon 18 July 1675.'

The most immediately striking thing about the figures is Swammerdam's rich use of colour, in the form of either water-colours or coloured inks. Swammerdam's other extant drawings were either done in ink or were first sketched in sanguine, then completed in black ink or pencil.[84] Furthermore, at the beginning of *The Book of Nature*, in a section probably written in the late 1670s, Swammerdam wrote of his drawings:

> there is no necessity to illustrate them with colours. And we are confident, that our figures are so accurately executed, that it would be unpardonable to daub them with paint.[85]

Unpardonable, perhaps, but glorious nonetheless. The use of colour — especially the rich greens, yellows, and browns — brings the illustrations to life and provides a contact with Swammerdam's vision that is different from that of his detailed ink drawings, conveying some of the sense of wonder and beauty to which Swammerdam so often gave voice in his writings.[86] Also, as the only other researcher to have studied these drawings has put it, they 'seem to symbolise the golden age of entomology'.[87] Finally, they provide yet more proof that Swammerdam was a consummate draftsman who had a real feeling for his subjects, as well as a keen eye for anatomical detail.

Eleven drawings show intact insects giving the stages of the life cycle: three show the caterpillar (two side views — Figures 4d and w — and one ventral view — Figure 4s), one shows a moulting caterpillar sloughing its skin (Figure 4c), another shows a late caterpillar shortly before pupation (Figure 4b), while yet another shows the pupa emerging from the caterpillar (Figure 4d). Finally, there are four figures showing the early and late pupa (Figures 4f–i) and a drawing of the adult moth (Figure 4k). These figures are executed in the free and elegant style that characterizes

[83] L. Belloni, 'Stensen-Andenken in Italien', *Analecta Medico-Historica*, 3 (1968), 171–180. See also L. Belloni, *Opere Scelete di Marcello Malpighi* (Turin, 1967).

[84] For example, his drawings for *The Book of Nature*. See F. J. Cole, 'The "Biblia Naturæ" of Swammerdam', *Nature*, 165 (1950), 511. See also Figure 7a.

[85] J. Swammerdam (note 45), I, 30. Swammerdam may well have been referring to the practice of hand-painting copper engravings in books: because of the lack of subtlety involved, this often obscured more than it clarified. For example, the plates in the first volume of Goedart's *Metamorphosis et Historia Naturalis Insectorum* (1662–69) (note 36), which are often hand-coloured, are not very informative, because of the thickness of the paint and the lack of tonal variation.

[86] For a discussion of this aspect of Swammerdam's science, see M. Cobb (note 39).

[87] L. Belloni (note 83, 1967), p. 35.

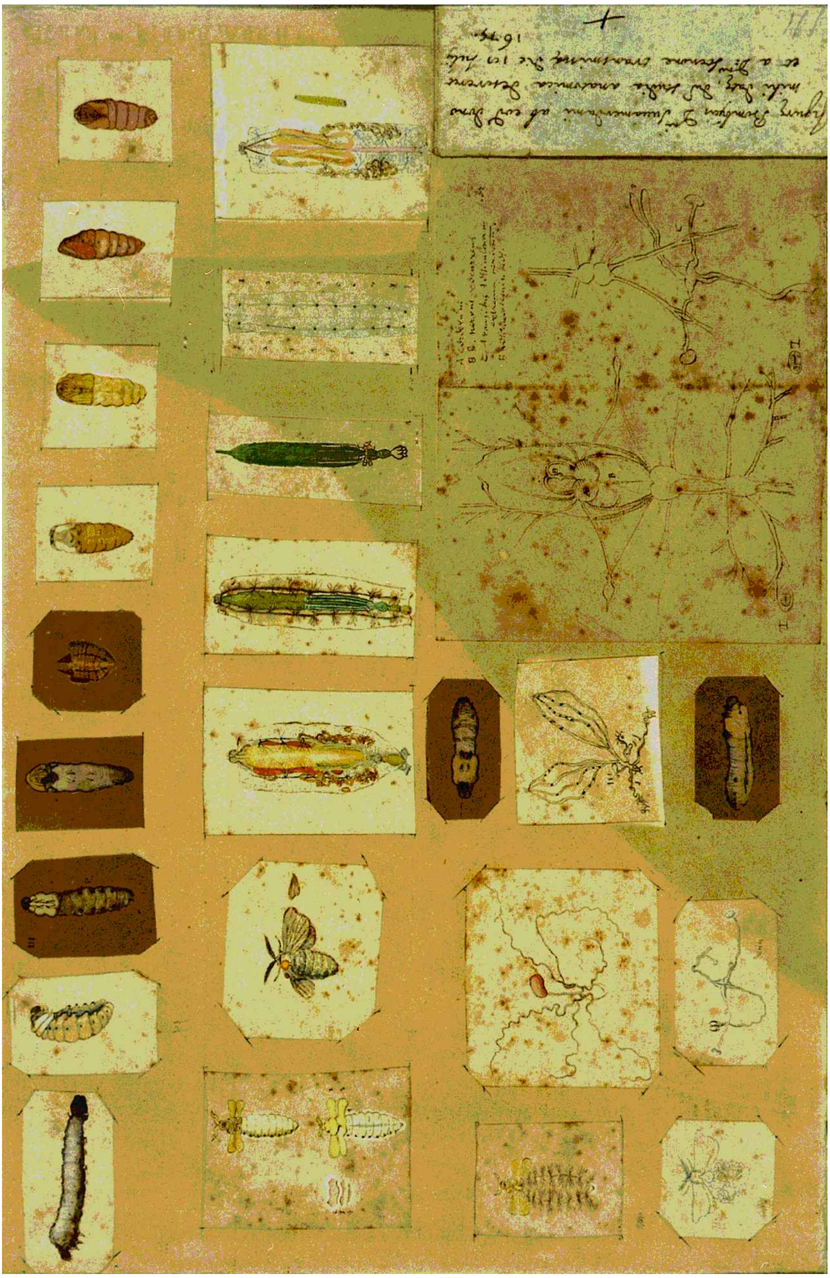


Figure 4. Swammerdam's illustrations of the silkworm, sent to Malpighi in July 1675. The original format is 26 cm × 40 cm. The hand-written legend reads in translation 'Drawings of Bombyx done by Master Swammerdam, which he gave to me because he was abandoning his studies of anatomy, and which were transmitted by Master Stenon 18 July 1675.' Reproduced with permission of the Università degli Studi di Bologna – Biblioteca Universitaria. All unauthorized reproduction forbidden.

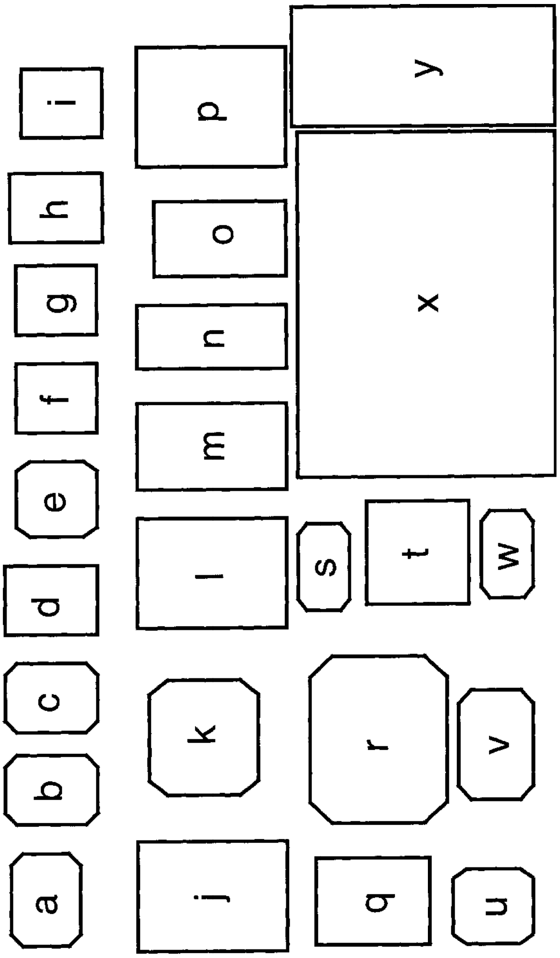


Figure 5. Annotation of illustrations shown in Figure 4.

Swammerdam's sanguine-and-ink drawings of whole insects, but with the added dimension of colour. Five other drawings show dissections of the caterpillar, including the tracheae and respiratory system (Figure 4o numbers the nine tracheal ramifications), the salivary and silk glands (orange — Figure 4l — or pink — Figure 4p), and the green gut, both *in situ* (Figure 4m) and dissected out (Figure 4n).

The remaining drawings show two dissections of what appear to be very late caterpillars (Figure 4j shows ventral and dorsal views of some of the adult forms that can be found immediately prior to the appearance of the pupa — wings, antennae, and legs), a dissection of what is apparently an abdominal section of the pupa (Figure 4d), and dissections of the respiratory system in the caterpillar (Figure 4q) of the reddish adult crop (Figure 4r) and of what are now known as the Malpighian tubules (Figure 4u). Two figures show dissections of the male and female genitalia (Figures 4v and s respectively — the former carries the word 'penis'). The largest illustration (Figure 4x) consists of two ink drawings, one of the larval nervous system and brain, the other the interaction between the male reproductive system and the larval nervous system (the testes appear in the caterpillar prior to pupation). This final drawing, which is faded and foxed, also carries a legend in Latin (see Figure 6). The left-hand illustration shown in Figure 6 shows the caterpillar brain, which Swammerdam had accused Malpighi of overlooking; the right-hand drawing shows something striking that neither man had previously commented on,

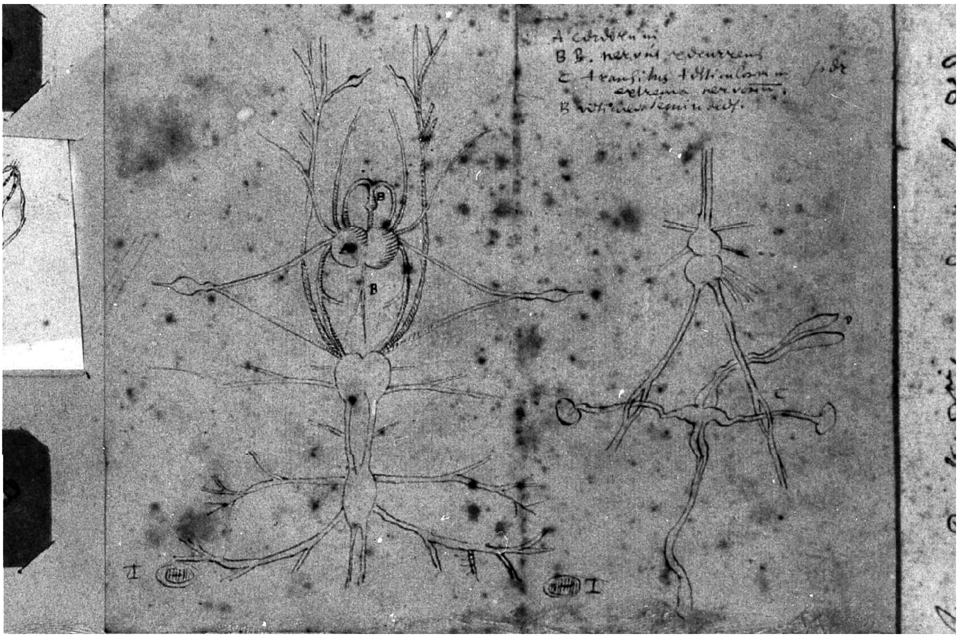


Figure 6. Swammerdam's drawings of the nervous system and male genital tract of the silkworm caterpillar sent to Malpighi in 1675. The left-hand figure shows the brain. The right-hand figure shows the final ganglion and the relation of the nervous system with the male testicles (already present in the caterpillar). The legend, in Swammerdam's hand, reads 'A Cerebrum, BB. nervus recurrens, C transitus testiculorum par extrema nervorum, D vesiculae seminales'. 'I' on both figures refers to the position of the nearest respiratory spiracle. Reproduced with permission of the Università degli Studi di Bologna – Biblioteca Universitaria. All unauthorized reproduction forbidden.

but which obviously intrigued Swammerdam (see Section 9): the bifurcation of the most posterior nerves around the vas deferens leading from the testicles.

Why did Swammerdam send these particular drawings to Malpighi? The choice of figures seems strange if all that Swammerdam wanted to do was to convince Malpighi of the superiority of his observations. Although the single large ink drawing of the larval nervous system clearly had this as its aim, it is difficult to see what polemical or pedagogical point is being made by, say, the drawings of whole caterpillars and pupae, or even by the two drawings showing the dissection of the gut. Furthermore, none of the drawings shows the caterpillar heart, which Malpighi asserted was multiple and Swammerdam (correctly) considered was not. Matters become slightly clearer if it is remembered that this is only part of Swammerdam's work. The rest of the manuscript, which may have contained more drawings and certainly contained his explanation of these figures, was destroyed. We are therefore left with a glimpse into what might have been Swammerdam's *De Bombyce* — from this point of view the choice of subjects does not seem quite so odd: like Malpighi, Swammerdam would have had to explain the basic anatomy of the silkworm to his readers.

However, even from this perspective, it is not clear what Swammerdam intended by the use of colour, which is clearly informative. Had Swammerdam been preparing material directly for the printer, he would undoubtedly have used the *grisaille* technique, which he mastered well. This suggests that the water-colours were intended either for his own personal clarification or to impress the person who saw them. Swammerdam might not, however, have thought of Malpighi initially: on the two points of difference dealt with in the drawings — the larval nervous system (Figure 4x) and the male genitalia (Figure 4v) — Swammerdam used colour sparingly (genitalia) or not at all (nervous system). In the only previous cases where Swammerdam employed colour — in the plates to *Miraculum Naturae*, and in some illustrations to a letter on the frog heart that can be found in the Royal Society archive[88] — it was used merely to highlight the presence of certain blood vessels. Here, however, Swammerdam is clearly trying to convey a realistic impression of the internal organs of a silkworm (there is no indication that stains or inks were used in the dissection). The changing colour of the caterpillar and pupa (described by Malpighi in *De Bombyce*) is correctly presented, and the different colours of the various structures are accurately portrayed. However, what Swammerdam expected Malpighi to make of it all (apart from the line drawings) is hard to determine.

As with the silkworm water-colour attributed to Malpighi earlier on, we are therefore left with an enigma: a strikingly beautiful one, but an enigma nevertheless. Perhaps the only satisfactory explanation resides in Swammerdam's mental turmoil at the time, expressed in his desire to break with what he considered to be the 'vanity' of the scientific world and his simultaneous craving for recognition from that same world. He therefore sent Malpighi — one of the few people who could completely understand it — either all that he had or the best that he had, or both, in what at the time he felt would be a final gesture of respect to the man who had clearly inspired him.

9. A dialogue divided

From this point on, there was no further contact between Malpighi and Swammerdam. Indeed, Swammerdam had less than five years to live. When he

[88] J. Swammerdam, 'Letter to H. Oldenburg 14.3.1673', Royal Society Letter Book 6, 57–58. A black and white reproduction can be found in A. R. Hall and M. B. Hall (note 63), Plate II.

emerged from the Bourignon cult in June 1676, disillusioned for unknown reasons, Swammerdam re-entered into contact with Thévenot and Oldenburg. Both men encouraged him to continue his work, and Swammerdam, perhaps spurred on by intimations of mortality due to his recurring bouts of malaria, began to assemble what he described as his 'great work'.[89] During this final period of intense scientific investigation, Swammerdam revisited much of his previous work, including his dissections of the silkworm, rendering his criticisms of Malpighi more precise. Malpighi, however, knew nothing of all this. Similarly, Malpighi replied to the criticisms advanced by Swammerdam in *Miraculum Naturae* — over the larval brain, the respiratory system, and the genitalia — in his *Opera Posthuma* (1697), published after both men were dead.

Therefore although after 1675 the 'debate' between the two men took on a strange form — the protagonists were unaware of each other's work — nevertheless it did continue, indicating that both scientists thought it was important and that they each valued the good opinion of the other — as well as of posterity.

Swammerdam enriched his description by explicitly introducing a comparative aspect, when he compared the silkworm's anatomy with that of the rhinoceros beetle, probably in late 1677.[90] Swammerdam found that, despite important differences, the fundamental organization of the nervous system was identical in the two insects. In so doing he noted an important feature of the organization of the gut and the nervous system in invertebrates, without realizing quite how general it was: 'the gullet passes through an opening of the marrow in Silkworms: this the famous Malpighius has neither described not delineated.'[91] Using very straightforward and unpolemical language, much more relaxed than that which characterized *Miraculum Naturae*, Swammerdam repeated his suggestion that Malpighi had simply overlooked the brain, but added, as though to mollify Malpighi and to put his criticisms into perspective, 'it is easy to add to what has been discovered before'.[92]

To back up his descriptions, Swammerdam included a figure that combines several of the features shown in the drawings he sent to Malpighi. Despite speculation to the contrary,[93] this is clearly a new drawing, presumably based on new dissections. Figure 7a shows the original ink drawing, Figure 7b the (reversed) printed plate. Both the drawing and the accurate engraving are more detailed and give a stronger impression of precision than those of Malpighi (Figures 2). Swammerdam gave a clear illustration of the brain and the posterior nerves bifurcating around the vas deferens, as well as the many projections from the posterior ganglion, and allowed himself the following anthropomorphic speculation:

> there are two of these nerves very remarkable *pp*, which I would have the reader seriously and repeatedly consider: they are perforated *ss* in a wonderful manner by the vassa differentia of the testicles of the Silk-worm Butterfly *rr*. But whether this conduces to pleasure in this species of insects, or to any other use, I leave others to determine.[94]

Malpighi's work on the silkworm can be divided into four periods: the initial investigations of autumn 1667, the research summarized in *De Bombyce* (spring

[89]For example, J. Swammerdam, 'Letter to Thévenot (30.3.[1678])', G. A. Lindeboom (note 53), p. 95.
[90]J. Swammerdam, 'Letter to Thévenot (4.11.1677)', in G. A. Lindeboom (note 53), pp. 70–74.
[91]J. Swammerdam (note 45), I, 138
[92]J. Swammerdam (note 45), I, 138.
[93]For example, L. C. Miall (note 82), L. Belloni (note 83, 1967).
[94]J. Swammerdam (note 45), I, 139.

1668), some studies of the stomach and silk gland (January 1671),[95] and his dissections in reply to Swammerdam's criticisms over the male reproductive organs (July 1689).[96]

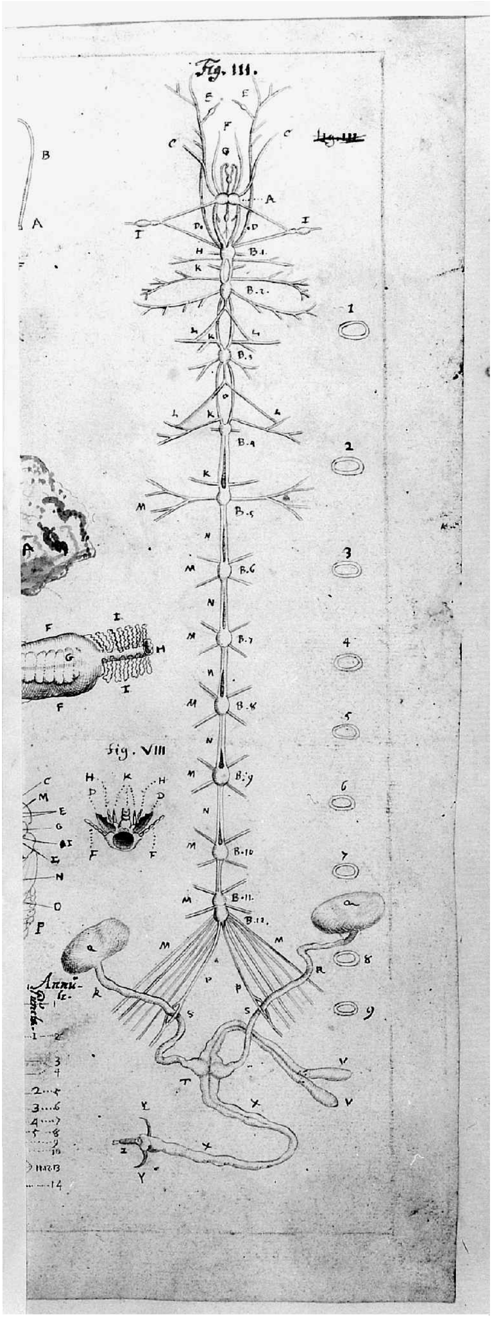
Malpighi's posthumous response to Swammerdam's criticisms of 1671–75 was prefaced by a reproduction of the two letters from Steno (1671 and 1675) cited above, the latter of which accompanied Swammerdam's figures. He then made the following declaration: 'I have decided to explain these figures of Swammerdam's so that the learned world may compare the studies the two of us have made and learn whether the things he detected are more important.' He continued, in an eerie echo of Swammerdam's own posthumous acknowledgement of who had priority in the matter, 'I beg the reader to remember that I was the first to enter upon this new and unknown territory, whereas Swammerdam had the advantage of knowing of my earlier studies.' Malpighi then explained that 'some of the things Swammerdam objected to as erroneous were in accord with Nature, and he attacked other things too sharply, so that I will spend some time examining the points of difference, not ungratefully to condemn the gifts of so great a man, but to reveal the truth in friendly discussion.'[97]

In his *Opera Posthuma*, Malpighi presented a new figure together with five paragraphs of explanation, focusing on the organization of the male genitalia in various animals, showing that he was right and Swammerdam was wrong. On the question of the larval brain, however, Malpighi was on less solid ground. Although this structure is very small, he had been able to describe it in his initial dissections of the silkworm in Autumn 1667, prior to receiving Oldenburg's invitation.[98] Despite bravely stating that 'if the reader is attentive and generous towards what is presented in my description, it will be obvious that I did in fact indicate and represent the mass of the brain',[99] Malpighi had to admit that the figure in *De Bombyce* does not show the brain (compare Figure 2 with Figure 6 or 7), which was omitted for reasons of space. Malpighi concluded by stating that 'both Nature and Dr Swammerdam himself agree' with his findings, and by pointing out that Swammerdam had made a similar error in his *Ephemeri Vita*, where the final, cerebral, ganglion of the mayfly nymph appears to be no different from the other ganglia.

10. Replication and the silkworm

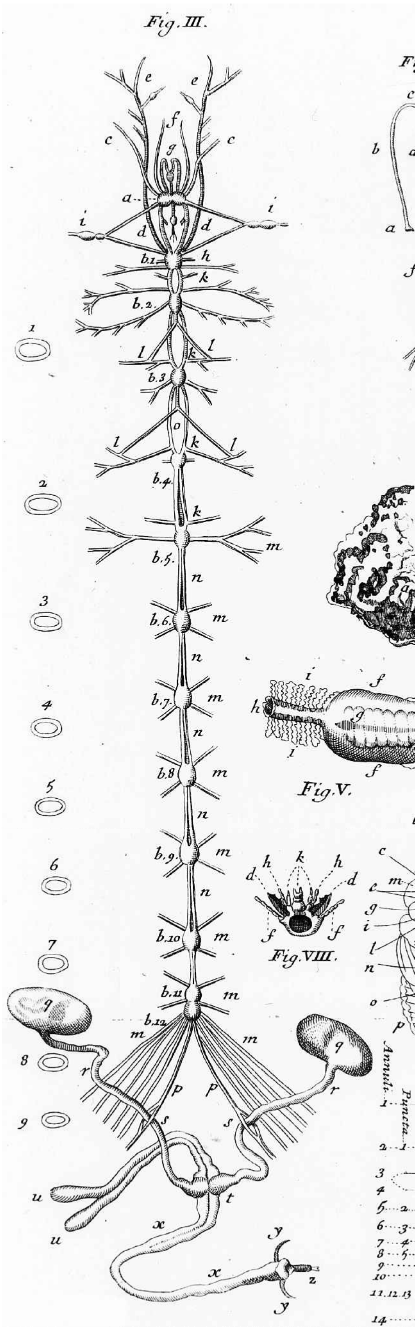
Although the simple question of who was right — Malpighi or Swammerdam — over which issues in their debate was undoubtedly important for science's history, for our increasingly accurate understanding of material reality, it is clearly of less importance for the history of science. After all, somebody, somewhere, somewhen, was inevitably going to provide a fully accurate description of the anatomy of the silkworm. The most interesting questions therefore relate to the reasons why the two men reported different results, the procedures they adopted, either directly or indirectly, for arriving at a common conclusion, and what this study can tell us about the development of early modern science as a whole.

[95] H. Adelmann (note 5), 357.
[96] H. Adelmann (note 5), pp. 592–93.
[97] M. Malpighi (note 14), p. 57. E. G. Ruestow (note 2), p. 122, has suggested that Malpighi's 'offended response reflected in part his own touchy sensitivity'. In fact, Malpighi's opening declaration appears to be marked by a high degree of courtesy.
[98] H. Adelmann (note 5), p. 327.
[99] M. Malpighi (note 14).



(*a*)

Figure 7. Swammerdam's drawings of the nervous system of the silkworm caterpillar, published in his posthumous work *Bybel der Natuur* (1737–38) as Table XXVIII, Figure III, and probably executed in 1677. The original caption is over 1500 words long and is preceded by the following description: 'The spinal marrow of a Silk-Worm when about to enter the Nymph state, the better to show the difference between its spinal marrow and that of the Cossus. As likewise what little reason some people have to



(*b*)

consider every dilatation of the marrow as a distinct brain.' (*a*) Original ink drawing. © Leiden University Library, MS BPL 126B fol. 2g^{R}. Reproduced with permission. (*b*) Unsigned (reversed) engraving. © Bibliothèque Inter-Universitaire Medicale, Paris. Reproduced with permission. There are no perceptible discrepancies between the drawing and the printed version, apart from a line missing from one of the projecting nerves 'm' after it passes under the 'vas deferens r-s' on the right-hand side of the engraving.

The reasons why the two men saw different things are relatively plain. This was an extremely difficult technical task, for three reasons. Firstly, the single-lens microscope was a very difficult apparatus to use effectively. It required the object to be continually brought in and out of focus in order for a full view to be obtained and, ideally, to be fitted out with flexible arms that could hold both lens and object.[100] Dissection could not take place under the highest-power lens, which virtually had to touch the object.[101] This therefore implied placing the dissected object under another lens, with all the attendant dangers of changed orientation, disposition, etc. Both men commented on the difficulty of dissecting using the microscope and the danger of seeing things that were not there.[102]

Second, the techniques and tools involved had to be invented — twice over, given Malpighi's lack of clarity on the subject. It would clearly be surprising if both men arrived at the optimum approach at their first attempt. Finally, and probably most importantly, because these were the first such dissections, neither man knew what to expect. Swammerdam certainly had the advantage of being second, but the edifice of comparative anatomy was still extremely shaky, and each man could only really trust his own eyes. Slight differences between preparations, or in the techniques involved, plus the different interpretative frameworks used by the two pioneers, could thus easily explain why they did not report seeing exactly the same thing.

The two men intuitively recognized that the only way of testing the other's observations was to repeat them. In doing so they were contributing to what Shapin and Schaffer[103] have argued was a key feature of experimental knowledge production — the importance of replication. Both Swammerdam and Malpighi carried out more than one set of dissections of the silkworm — in 1667–68, 1671, and 1689 for Malpighi, in 1670–72 and probably in 1677 for Swammerdam. In Swammerdam's case, both sets were aimed at testing the validity of Malpighi's observations by repeating them; for Malpighi, the objective was literally to replicate his observations faced with Swammerdam's criticisms. This was clearly costly in terms of time and effort (in particular for Malpighi, who carried out his final dissections at the age of sixty-one), and flowed from the reliance on material proof rather than on authority or rhetorical skills for clinching an argument.

In order to replicate, however, the techniques involved in making the discovery need to be communicated. As we have seen, Malpighi, to Swammerdam's evident annoyance, did not share this concern, at least in the pages of *De Bombyce*. In other publications, both before and after *De Bombyce*, Malpighi was more forthcoming. For example, in *De Pulmonibus* (1661) he recounted how he used microscopes of different powers, using different techniques for illuminating the object. He also gave summary descriptions of the techniques he used for preparing the material (desiccation, boiling, blowing into the lungs, draining blood, etc.),[104] and in 1665 he explained

[100]Musschenbroek made such a device for Swammerdam. H. Boerhaave (note 82), p. xiv.

[101]J. Swammerdam, 'Letter to Thévenot (January 1678)', in G. A. Lindeboom (note 53), p. 83.

[102]H. Adelmann (note 5), p. 370. J. Swammerdam (note 45), I, 37.

[103]S. Shapin and S. Schaffer, *Leviathan and the Air-Pump: Hobbes, Boyle, and the Experimental Life* (Princeton, 1985). Although I strongly disagree with what appears to be the methodological basis of the authors' analysis, as expressed by their view that 'it is ourselves and not reality that is responsible for what we know' (p. 344) — in fact it is both reality and ourselves that are responsible — and that science is bounded by 'conventions' which by implication may be arbitrary and do not necessarily have a material basis, their book clearly set a bench-mark for studies of the development of early modern science.

[104]L. Belloni, 'Marcello Malpighi and the founding of anatomical microscopy', in *Reason, Experiment, and Mysticism in the Scientific Revolution*, ed. by M. L. R. Bonelli and W. R. Shea (London, 1975), pp. 95–110.

how he stained the brain using ink,[105] while in the first part of his study of plant anatomy (1675) he explained his techniques for cutting sections and for making drawings.[106] In *De Bombyce*, however, he did not even describe the kind of microscope he used (single lens or compound). Other microscopists were similarly silent on such matters — for example, Leeuwenhoek provided poor information as to how he carried out his observations,[107] and Frederic Ruysch, whose technique for injecting wax into organs surpassed Swammerdam's, never gave a full account of his methods.[108]

Swammerdam's evident frustration faced with Malpighi's failure to explain exactly how he carried out his dissections may have played a decisive role in Swammerdam's subsequent emphasis on explaining his techniques. In this respect, Swammerdam's work shows a substantial evolution. For example, *Historia Insectorum Generalis* (1669) contains only one passage relating to his methods, in which he advises the use of different coloured backgrounds to observe insects in drops of water, without even stating what form of magnifying device he employed. His subsequent work, summarized in *The Book of Nature*, was characterized by repeated methodological digressions, in particular on the virtues of the single-lens microscope, which formed part of the basis of Swammerdam's centuries-long fame. It seems most likely that this change was at least partly a consequence of Malpighi's failure to provide such information. There may also be a psychological explanation to this feature of Swammerdam's science, rooted in his undoubted (and justified) pride in his work, which at least in some phases of his existence he also considered to be a terrible sin.[109] In 1678, Robert Hooke was similarly provoked by Leeuwenhoek's failure to explain his techniques to publish a short account of microscopical techniques, *Microscopium*.[110] Clearly, Swammerdam, and on this occasion Hooke,[111] were helping to forge aspects of science's mode of functioning that persist to this day and which provide an essential part of its ability to check, affirm, and refine knowledge on a systematic and conscious basis.

11. Visual representation and the silkworm[112]

The decisive and most striking elements of this story are the figures — the sanguine or ink originals, the black-and-white engravings and the unique water-

[105] M. Fournier (note 3), p. 113.
[106] D. B. Meli, 'The new anatomy of Marcello Malpighi', in D. B. Meli (note 40).
[107] M. Fournier (note 3), p. 34.
[108] E. Ruestow (note 2), p. 86.
[109] For examples of Swammerdam's tortured attitude towards his research, see E. Ruestow (note 2).
[110] M. Fournier (note 3), p. 34.
[111] Hooke was not always so open, as shown for example in his contemporary dispute with Huygens over the balance-spring regulator for a watch. See L. Jardine (note 5), pp. 318–25.
[112] The question of the use and meaning of visual representations in science has been intensively studied over the last twenty to thirty years, but there appears to be no specific study of the development of natural history and anatomical illustrations during the seventeenth century. The following section can be considered as a first foray into this field. For a stimulating introduction to the study of scientific illustrations, see the articles in *Picturing Knowledge: Historical and Philosophical Problems Concerning the Use of Art in Science*, ed. by B. S. Baigrie (Toronto, 1996). For a discussion of the techniques involved in illustration and an initial classification of natural history illustrations, see D. Knight, *Zoological Illustration* (Folkstone, 1977). S. P. Dance (note 8) and B. J. Ford, *Images of Science* (London, 1992) contain some wonderful examples of the development of scientific illustration. F. J. Cole (note 16) also reproduces a wealth of images from comparative anatomy from this period, but his Whiggish emphasis is on accuracy, not style of representation. For a brief overview of the development of scientific illustration up to 1670, see C. M. Pyle (note 35). For a discussion of a similar problematic, see W. D. Hackmann, 'Natural philosophy textbook illustrations', in *Non-Verbal Communication in Science Prior to 1900*, ed. by R. G. Mazzolini (Florence, 1993), pp. 169–96. C. Wilson (note 3) discusses the philosophical problems

colours that both men produced. Illustrations played a multiple role in the work of Swammerdam and Malpighi.

Firstly, an illustration was an essential part of the 'experiment' in progress, helping the observer to see more clearly what they had discovered, by refining their perception of the object. In this sense, far from being passive reflections of knowledge, illustrations play a role in the definition and clarification of that knowledge prior to it being communicated.[113] Furthermore, repeated use of technique improved and honed that technique, as shown by the evolution of both Malpighi's and Swammerdam's illustrations, the later examples of which tended to have an economy of line which is more typical of modern approaches.[114]

Second, the engravings provided a proof of what was claimed to have been discovered. In this respect, they were clearly more effective that many purely verbal representations.[115] However, they were generally precisely illustrations of the text and were also accompanied by titles that could be extremely detailed (e.g. see caption to Figure 7). They thus gelled the discovery in the mind of the reader, transforming a report into an image, and, to an extent, coming to stand for the discovery itself.[116] Also, of course, they acted as a guide for subsequent investigators, framing what they expected to find, and thus making it easier to see. The 'proof' provided by an illustration thus simultaneously provided the basis for testing the discovery through replication. The image could also be considered as showing the kind of presentation that would be necessary for any challenge.[117] However, as Catherine Wilson has pointed out, especially in the case of microscopy, images did not necessarily explain anything; rather, they set out what had to be explained.[118]

Finally, such illustrations also valorized the research by presenting striking or beautiful images that both transmitted the scientist's aesthetic judgements (this was clearly the case with Swammerdam, whose writings abound with rapturous descrip-

associated with visual evidence in microscopy. Pointers to the kind of analytical approaches that will be needed can be found in P. J. Taylor and A. S. Blum, 'Pictorial representation in biology', *Biology and Philosophy*, 6 (1991), 125–34, A. S-K. Pang, 'Visual representation and post-constructivist history of science', *Historical Studies of the Physical and Biological Sciences*, 28 (1997), 139–71, and D. Topper, 'Towards an epistemology of scientific illustration' in B. S. Baigrie, pp. 215–49.

[113] C. M. Pyle (note 35).

[114] R. B. Freeman, 'Illustrations of insect anatomy from the beginning to the time of Cuvier', *Medical and Biological Illustration,* 12 (1962), 174–83. Robert Hooke appreciated what C. M. Pyle (note 35) has called the feedback of drawing and observing. As Hooke put it in the Preface to *Micrographia*, 'true philosophy' had to '*begin* with the Hands and Eyes, and to *proceed* on through the Memory, to be *continued by* the Reason; nor is it to stop there, but to *come about* to the Hand and Eyes again, and so by a *continual passage* round from one faculty to another, it is to be maintained in life and strength' R. Hooke (note 12), no page number.

[115] See for example Henry Power's opaque description of a bee's eye, cited in C. Wilson (note 3), p. 222.

[116] Shapin and Schaffer (note 103), p. 59, argue that such illustrations formed a way of accepting a discovery as objective, through what they call 'virtual witnessing'. This view requires two critical corrections. First, on a general level, scientific results that are reported at a distance (i.e. in literary or graphic form) — virtually all the science that is carried out today and a good part of that carried out in the seventeenth century — are finally accepted or rejected (i.e. accepted as objective) according to whether they can be replicated. Reports that appear fantastic or at too great a variance with current knowledge may be initially doubted, but the only decisive argument against them will be a better experiment, set of observations, or interpretation. Second, Shapin and Schaffer argue that the 'circumstantial detail' in engravings showing the air-pump helped to convince the reader of the efficacy of the apparatus. Whether they are right or not in this specific example, their argument does not hold for the larger class of anatomical illustrations: as shown below, such drawings precisely leave out 'circumstantial detail' which would confuse, not clarify.

[117] This final aspect is one of the few useful points made in B. Latour, 'Drawing things together', in *Representation in Scientific Practice*, ed. by M. Lynch and S. Woolgar (Cambridge, 1990), pp. 19–68.

[118] C. Wilson (note 3).

tions of what he saw) and also reflected the researcher's skill either directly (as in the case of Swammerdam and Malpighi who made their own drawings) or indirectly if someone else intervened (as for van Leeuwenhoek). This aspect was presumably important in the unique water-colours presented here in Figures 3 and 4, with the added aspect that, because of obvious limits on contemporary printing techniques, they could only truly be appreciated by those privileged enough to see them directly.

David Knight[119]and David Topper[120] have both argued that scientific illustrations are more or less 'theory laden'. The figures presented here would appear to belong to the 'less' end of the scale. The only 'theory' they embody is that insects have internal structures and that what can be seen through the microscope is true. At the time, of course, these were not trivial propositions, but more important — then and now — were the form and the empirical content of these illustrations and the interaction between the two aspects.

Malpighi's images presented in *De Bombyce* represent a clear breakthrough not only in what they represented (the internal organs of an insect) but also in how they were represented. In this respect, two points are important. On a personal level, for the first time Malpighi provided detailed and rich iconographic support for his written declarations — the forty-eight illustrations in *De Bombyce* are far more numerous and more detailed than those in his previous works (for example, in *De Pulmonibus* (1661), there are only five small images). On a more general level, Malpighi's drawings conformed to a model that was gradually to impose itself throughout biology.

The implicit message in the style of representation embodied by Malpighi's drawings and adopted by Swammerdam is that the illustrations are accurate, precise, and true — that the image that is presented is what another observer should be able to see. It might be expected that, given that the aim was to convince the reader, micro-anatomists would have continued the detailed, *trompe-l'oeil* style that particularly characterized Dutch painters of natural history such as de Gheyne. The opposite was the case, however. In their presentations to their readers — if not in the two unique examples of the use of colour presented here in Figures 3 and 4, first Malpighi and Swammerdam, and then their scientific successors, broke with 'naturalism' and used a technique that was very different from that adopted by their artist predecessors.

Strictly speaking, Malpighi and Swammerdam did not draw what they saw, or rather, they did so in a Platonic sense — showing the essence of what was present under the lens — rather than in a literal one. Both Swammerdam and Malpighi explained that in order to show the reader what was really there, they had chosen to emphasize certain parts of what they saw at the expense of others. This took on several aspects.

Firstly, like their medical anatomist predecessors, they did not portray fat, which in reality clings to organs and tends to hide internal structures, or, on a more trivial level, blood or other internal fluids which flow freely in inevitably messy dissections. Second, both men deliberately selected what they represented and how it was to be shown. In *The Book of Nature* Swammerdam wrote 'Indeed, in my figures I have not always observed the proportional magnitude of the parts, since I looked upon

[119]D. Knight, 'Scientific theory and visual language', in *The Natural Sciences and the Arts: Aspects of Interaction from the Renaissance to the Twentieth Century*, ed. by A. Ellenius, Acta Universitatis Upsaliensis Figura Nova Series 22 (Uppsala, 1985), pp. 106–24.

[120]D. Topper (note 112).

that as a work of great labour and little use, and therefore I have not scrupled sometimes to delineate one part larger than another',[121] while in 1679 Malpighi said of his drawings 'they do not depict distinctly all the parts of the object which are truly extant because by outlining any minute detail the figures would become almost measureless [...] I produced the figures enlarged and, without neglecting natural integrity, changed the layout, separating the parts.'[122] Furthermore, where results are uncertain or ambiguous, a drawing tends not to express that ambiguity, but rather to illustrate only one possible interpretation.[123] This highlights the importance of the fact that these figures illustrated a text and were not meant as, or taken as, stand-alone scientific objects.[124] Finally, as we have seen in the case of Malpighi's failure to show the silkworm's brain because of lack of space, technical limitations could lead to erroneous representations.

The 'editing' of what could be seen under the lens took on an even more striking form in the way that the dissected parts of the insect's body were presented as being separate from the rest of its anatomy. This process was essentially an adaptation and reinforcement of a form of representation that had begun to be adopted in medical circles following Vesalius' 1543 book of anatomy, *De Fabrica*, in which isolated bones and organs are shown without any reference to scale or to the rest of the body.[125] Prior to Malpighi, the earliest practitioners of comparative anatomy, Casserius, Fabricius, and Severino (all Italians), had presented organs isolated from the rest of the animal's body.[126] Malpighi took this process a step further, with his detailed engravings and his novel subject. The importance of this reductionist objectification of the body's components is that, by (literally) focusing the reader's attention on what is essential, the artist is able to impose his or her view, removing all that is superfluous. However, this also had a major negative consequence: faced with an utterly novel — and often bizarre — structure, the reader had no way of putting the organ into context or even determining its size.[127] This is clearly even more problematic in the case of the minute structures of an insect.

As well as effectively abstracting the organ from the animal, the new style of representation also abstracted the animal from its environment.[128] None of the illustrations in *De Bombyce* shows the silkworm as an organism in the world. This is very different from Swammerdam's work in *Historia Generalis*, where, for example, he shows water fleas and mosquito larvae in the water and a caterpillar crawling on a plant. In *The Book of Nature*, however, the only new material that contains any

[121]J. Swammerdam (note 44), I, 111.

[122]Translated by D. B. Meli in D. B. Meli (note 106), pp. 55–56. Meli suggests that this may also be a veiled response to Swammerdam's criticisms of his drawings in *De Bombyce* (see section 6).

[123]C. Wilson (note 3).

[124]This point is emphasized by both D. Knight (note 119) and D. Topper (note 112).

[125]K. B. Roberts and J. D. W. Tomlinson, *The Fabric of the Body: European Traditions of Anatomical Illustration* (Oxford, 1992). At least some of the drawings in Vesalius' book were drawn by Jan Stefan, a pupil of Titian.

[126]See F. J. Cole (note 16) for examples of their work. However, unlike Malpighi, their work was not monographic, but tended to focus on a variety of mammals and a few large invertebrates. The impact of their dissections and of the presentation of their discoveries was therefore less than that of Malpighi. They also made some important mistakes. For example, the ever-generous F. J. Cole (note 16), p. 141, describes Severino's dissection of the squid as a 'formidable list of hapless guesses'.

[127]E. H. Gombrich, 'Mysteries of Dutch painting', *The New York Review of Books* (10 November 1983), 13. E. G. Ruestow (note 2), p. 75, argues that this lack of familiarity militates against the illusion of reality expressed in such figures. However, part of the power of art is that the human eye can accept as real something that it has never seen before.

[128]Vesalius placed 'his' bodies in classic poses against backdrops of ruins, forming a continuous frieze from plate to plate.

reference to the animal's natural history is the section dealing with gall wasps. Swammerdam's *Ephemeri Vita* (1675) clearly shows this change in style, with the illustrations that were apparently made in the late 1660s — those that do not show dissections and which did not require a microscope — showing mayflies sporting in the water, complete with fish and birds, whereas the dissections, made in the first half of the 1670s, are all illustrated in a sparse style. Another aspect of this partial passage from drawing to diagram is the use of letters to denote various organs. Again, Swammerdam's evolution demonstrates this: in *Historia Generalis*, there are no letters on the figures; by the time he prepared the same figures for inclusion in *The Book of Nature*, he had adopted Malpighi's style and included explanatory letters denoting various body parts on a large number of the figures.

The new style of illustration involved abandoning two artistic conventions linked to 'realistic' representations: dark backgrounds and, although not quite so systematically, shadows. Although the artist who painted the caterpillar water-colour shown in Figure 3 followed one of the conventions of still-life painting by placing the silkworm on a dark background (as did Swammerdam in some of his illustrations shown in Figure 4), Malpighi did not employ this practice in his figures in *De Bombyce*. Swammerdam clearly felt the influence of Malpighi, for, although many of his drawings in *Historia Generalis* are given black backgrounds, he turned against this procedure a year or so later,[129] and none of his later illustrations shows this technique. Similarly, although both artists such as de Gheyne and natural historians such as Hoefnagel[130] used shadows to give a *trompe-l'oeil* impression that the insect was resting on the page, this procedure was used only sparingly by Swammerdam and not at all by Malpighi. Shadows were of course included on the figures, in order to give an impression of depth, but this is different in both intention and execution. Finally, the organisms that appeared in the illustrations were there in their own right: they were not emblems or symbols. Also, although earlier in the seventeenth century powerful symbolic reasons may have lain behind the choice of certain subjects, this factor clearly wore off as the 'scientific revolution' proceeded.

In her study of seventeenth century Dutch art, Svetlana Alpers[131] argues that there was a major difference between Dutch and Italian painting, in that the Dutch approach tended to emphasize direct visual representation rather than reference to a holy or classical text. She also suggests that Dutch eyes found it easier to trust what they saw through the microscope because the art that surrounded them was detailed and realistic.[132] Edward Ruestow, on the other hand, has suggested that Dutch naturalistic artistic traditions actually militated against the adoption of the microscope.[133] The evidence presented here apparently indicates that Ruestow is correct: not only did Malpighi, not Swammerdam or Leeuwenhoek, pioneer the use of the microscope to reveal hitherto unsuspected structures, he also developed a graphic style that represented and required a break with the Dutch realist tradition,

[129]In autumn 1670, Swammerdam discussed the possibility of a French translation of *Historia Generalis*, and suggested changing the plates: 'one should have all the little animals cut without the brown backgrounds: this would not only be less expensive, but would give less trouble too.' J. Swammerdam, 'Letter to Thévenot (30.10.1670)', in G. A. Lindeboom (note 53), p. 58.

[130]D. I. Hoefnagel, *Diversae insectorum volatilium ad vivum accuratissime depictae* ([n.p.], 1630).

[131]S. Alpers, *The Art of Describing: Dutch Art in the Seventeenth Century* (London, 1983).

[132]Alpers' argument is partly based on a poor grasp of the history of the use of the microscope. Her starting point is that Leeuwenhoek 'was amazingly the first, and for a while the only, man in Europe to pursue the study of what was seen in microscopic lenses.' S. Alpers (note 131), p. 25.

[133]E. Ruestow (note 2).

and which Swammerdam clearly adopted. However, it would require more serious analyses of contemporary responses to microscopic images, in a variety of European countries, and a comparison with more structural explanations of Malpighi's initiative (see Section 2) before Alpers' aesthetic explanation of this piece of scientific progress could be accepted or rejected.

12. Conclusion

This exchange between two of the founders of modern biology is revealing in a series of ways. On an immediate level, it shows the impact of Malpighi's pioneering investigation of insect anatomy and the way in which this study shaped Swammerdam's work, in terms of his subject, his methods, and his communication of his techniques. More generally, it reveals how some of the key features of modern science began to appear in the early modern period, in particular the importance of replication as a way of testing reported results and the development of a detached and objectified style of representation in which individual organs or structures are presented without reference to the organism, and the organism is presented without reference to its environment. The study also casts light on the form taken by relations between scientists at this time, both in terms of the way in which they communicated (or not) and the terms they used when referring to each other. Also, it underlines the role played by the Royal Society, and in particular by Henry Oldenburg, in encouraging and attempting to co-ordinate the work of the two men.

However, the most striking features of the whole story are the water-colour to be found in the manuscript sent by Malpighi to the Royal Society and the set of drawings sent by Swammerdam to Malpighi, both marked by a brilliant and unprecedented use of colour. Studies of visual representation in scientific illustrations have often concentrated on the final, printed version, which constituted the primary method by which this aspect of scientific discovery was communicated. However, as these two examples show, the early anatomists did not see the world in black and white. In these paintings, Malpighi and Swammerdam were able to communicate directly their perception of colours, even though only to a few individuals. However, in their written descriptions, both men described the colours of what they saw. This suggests that, even in the absence of colour illustrations such as those presented here, a purely textual study of the role of colour in early modern science could nevertheless be revealing. For the moment, however, we are left with these striking illustrations which speak directly to us down the centuries, revealing a new facet of their makers' vision of the natural world.

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