

Monuments and Microscopes: Scientific Thinking on a Grand Scale in the Early Royal Society

Author(s): Lisa Jardine

Source: *Notes and Records of the Royal Society of London*, May, 2001, Vol. 55, No. 2 (May, 2001), pp. 289-308

Published by: Royal Society

Stable URL: <https://www.jstor.org/stable/532102>

JSTOR is a not-for-profit service that helps scholars, researchers, and students discover, use, and build upon a wide range of content in a trusted digital archive. We use information technology and tools to increase productivity and facilitate new forms of scholarship. For more information about JSTOR, please contact support@jstor.org.

Your use of the JSTOR archive indicates your acceptance of the Terms & Conditions of Use, available at <https://about.jstor.org/terms>



JSTOR

Royal Society is collaborating with JSTOR to digitize, preserve and extend access to *Notes and Records of the Royal Society of London*

MONUMENTS AND MICROSCOPES: SCIENTIFIC THINKING ON A GRAND SCALE IN THE EARLY ROYAL SOCIETY†

by

LISA JARDINE

*School of English and Drama, Queen Mary, University of London,
London E1 4NS, UK*

On 25 August 1664 (almost exactly two years before the Great Fire of London) the curator of experiments for The Royal Society in London, Robert Hooke, wrote to the ‘father of modern chemistry’, Robert Boyle (for whom he did regular work as a paid designer and builder of experimental equipment), at his ‘elaboratory’ in Oxford, describing some scientific experiments he had carried out for The Royal Society a few days earlier:

I have since your departure been on the top of Paul’s steeple, in order to make several experiments, which will be prosecuted this week. But it being the first time I had been there, I could not be so well provided with apparatus as I found was requisite, and therefore I was fain to return with only making some observations.

One was, that a pendulum of the length of one hundred and eighty foot did perform each single vibration in no less time than six whole seconds; so that in a turn and return of the pendulum, the half-second pendulum was several times observed to give twenty-four strokes or vibrations.

Another was, that this long pendulum would sometimes vibrate strangely, which was thus: The greatest part of the line, by guess about six score foot of the upper part of it, would hang directly perpendicular, and only the lower part vibrate; at what time the vibrations would be much quicker, and this though there was a weight of lead hung at the end of the string of above four pounds weight.

In another place of the Tower, where I had very clear perpendicular descent, I with the plumb-line found the perpendicular height of it two hundred and four feet very near, which is about sixty feet higher than it was usually reported to be. In which place I shall, with some other company, this week try the velocity of descent of falling bodies, the Torricellian [barometer] experiment, and several experiments about pendulums and weighing.¹

Two weeks later Hooke wrote to Boyle again, with an account of the experiments he had conducted as promised at his ingeniously selected location:

The manner of making which experiment was thus: The steeple being without any kind of lofts, but having only here and there some rotten pieces of timber lying across it, I caused a rope to be stretched quite cross the top, and fastened; in the midst of which I fixed a pulley, through which I let down the string and weight to the bottom (for only in the very middle of the steeple was there a broad clear passage from top to bottom) and to this I could not at the top approach within eighteen foot.

† Lecture delivered at The Royal Society on 20 November 2000.

Having thus let down the rope, those that were at the bottom hung on this mercurial tube [the barometer] (which I had already marked and stopped, and set ready before I went up) a large weather glass (which moved by the rarefaction and condensation of the air only, which I had likewise marked and stopped) and a sealed thermometer, which I had likewise marked. After these were drawn up, and by the contrivance of another pulley I had drawn them to me, I found the thermometer, the glass being but thin, broken. The quicksilver, upon opening the cock, I found to fall very considerably, which since, upon measuring, I find $25/48$ of an inch. The weather-glass I found to be risen somewhat more than two inches.

Then closing them again, I caused them to be let down; and giving them charge not to let it quite down till I called to them from below, I went down myself, and found, upon opening the mercurial tube, that it rose exactly to its first station; as did also the weather-glass.

I had designed to have tried many others [other experiments] then, but the night came so fast, that I could hardly see to get up again, and give order for the clearing of the lines.²

A week later again, Hooke reported to Boyle that he had repeated the ‘Torricellian experiment’, and carried out more pendulum experiments at St Paul’s, this time with the President of The Royal Society, Lord Brouncker, and Sir Robert Moray in attendance (presumably safely at the bottom of the structurally precarious steeple). Boyle, in the meantime, wrote back to The Royal Society’s Secretary Oldenburg, magisterially suggesting various modifications to Hooke’s experiments and proposing some experiments of his own with magnetism, which might also be tried at the bottom and top of St Paul’s steeple—‘which experiments’, the records of The Royal Society tell us tactfully, ‘though esteemed considerable, yet were thought not practicable at the said steeple, by reason of the iron there mixed every where.’³

Of course, I have misled you—I hope the ‘steeple’ gave you a clue. We are not talking here about Sir Christopher Wren’s St Paul’s Cathedral, with its familiar dome, but about Old St Paul’s, which dominated London’s skyline in the first half of the 17th century.

Even so, I have misled you again. The steeple of Old St Paul’s collapsed in the 1560s. In 1664, Hooke was conducting his experiments precariously poised on the cross-beams of the derelict tower of the condemned church of Old St Paul’s. I take this story as my starting point, because I think it illustrates rather elegantly the way the worlds of arts and sciences (and the narratives we can produce—the stories we can tell—about them) are tangled together at the dawn of the so-called ‘scientific revolution’. The tale of St Paul’s Cathedral and Sir Christopher Wren (who’ll soon make an appearance in person) belongs to the history of architecture, aesthetics and beauty. The story of Robert Boyle and laboratory experimentation belongs to the history of science, to emerging chemistry and ‘Boyle’s law’ ($PV = \text{constant}$; where P is gas pressure and V its volume). In that story, Robert Hooke sometimes figures as the ‘technician’—the man who made Boyle’s ‘pneumatic engine’, in which he experimented with the effects of altered pressure, work (and some of you will associate him with precise time-keeping and the longitude problem, as well as with the elasticity of springs).

We begin, then, with an experimental scientist and a landmark London church. Today, one belongs, for us, to something called ‘history of science’, the other to ‘architectural history’. One field concerns itself with what is ‘technical’, the other with what is ‘artistic’, ‘creative’. What I am going to try to do is to show you how the map of intellectual innovation and influence alters if we think about scientific discovery,



Figure 1. St Paul's Cathedral. (© Guildhall Library, Corporation of London.)

technical invention and artistic creativity as always and inevitably inter-connected and cross-fertilizing. For Hooke and Boyle themselves, there appears to have been no disciplinary fracture between their activities, in which they participate as part of a seamless continuum. What does the history of creativity and innovation look like if we remove those relatively recent academic boundaries? What happens if today we recast creativity as a generalized energy, released under pressure of immediate demands and circumstances, through the efforts of engaged, problem-solving groups of people, operating between what have become for us competing disciplines, succoured by different specialisms?

We may start, though, with a more modest, more straightforward question: when The Royal Society proposed that Hooke find some elevated location 'in a place free from wind', to conduct experiments, what made him choose St Paul's?⁴ Well, it was conveniently accessible because he was already working there, part of a team assessing the structural state of the spire.⁵ One of the several paid jobs by which the modestly born Hooke made a living was as a skilled surveyor (notice how he reported to Boyle

that the height of the tower of Old St Paul's was greater than generally believed). In 1663, a government commission appointed to oversee the restoration of the cathedral had pronounced the building unsafe, and proposed that the damaged nave and the steeple be demolished. Christopher Wren (Professor of Astronomy at Oxford since autumn 1661, but already establishing himself as an architect with the Sheldonian Theatre at Oxford and as an advisor on the proposed fortification of the port of Tangier) was called in to give a second opinion.

The state of St Paul's was a matter of some symbolic importance to the restored monarchy of Charles II. The great Inigo Jones had partially completed a magnificent classicizing facelift for the cathedral for Charles I, before civil war made the project irrelevant (Inigo Jones died in 1652). During the Protectorate period, Oliver Cromwell considered turning the 'Crosse building of St. Paul's' into a fortified base for himself 'to bridle the City of London' (it stood, as indeed Wren's St Paul's does today, conveniently for surveillance purposes, on the only piece of high ground in the City). In those 'unfortunate times' (as Wren and Hooke would probably have called the 1650s), Jonas Moore (not yet knighted), future Surveyor to the Ordnance (what we could call the Ministry of Defence) under Charles II, reputedly constructed a feasibility model for such a citadel.⁶

In May 1666, Christopher Wren produced a report, accompanied by preliminary designs, proposing encasing and refacing the entire interior of the nave (as Inigo Jones had already done the exterior 30 years earlier), and enclosing the 'tower's world of Scaffolding poles' (from which presumably Hooke had hung his pulleys) with 'a spacious Dome or Rotunda, with a Cupola or hemispherical Lantern with a Spiring Top' rising 'proportionately' above it.⁷

In his diary entry for 27 August 1666, John Evelyn (gentleman amateur of classical architecture, diarist and fellow member of The Royal Society) records an on-site visit to St Paul's, following on from Wren's report:

I went to St. Paules Church in Lond: where with Dr. Wren, Mr. Prat, Mr. May, Mr. Tho. Chichley, Mr. Slingsby, the Bish: of Lond., the Deane of S. Paule, & severall expert Workmen, we went about to survey the generall decays of that antient & venerable Church, & to set downe the particulars in writing, what was fit to be don, with the charge thereof: giving our opinion from article to article: We found the maine building to recede outward: It was Mr. Chichleys & Prats opinion that it had been so built ab origine for an effect in Perspective, in regard of the height; but I was with Dr. Wren quite of another judgement, as indeede ridiculous, & so we entered it: We plumbed the Uprights in severall places: When we came to the Steeple, it was deliberated whither it were not well enough to repaire it onely upon its old foundation, with reservation to the 4 Pillars: this Mr. Chichley & Prat were also for; but we totaly rejected it & persisted that it requird a new foundation, not onely in regard of the necessitie, but for that the shape of what stood was very meane, & we had a mind to build it with a noble Cupola, a forme of church building, not as yet kowne in England, but of wonderfull grace: for this purpose we offerd to bring in a draught & estimate, which (after much contest) was at last assented to, & that we should nominate a Committè of able Workemen to examine the present foundation: This concluded we drew all up in writing, and so going with with [sic] my L: Bishop to the Deanes, after a little refreshment, went home.⁸



Figure 2. Sir Christopher Wren. (Royal Society portrait.)

Five days later Evelyn's scrupulous structural survey and Wren's report had both become irrelevant. During the night of 2 September 1666 and the five days that followed, the Great Fire of London gutted Old St Paul's and damaged beyond repair about seven-eighths of the City of London (395 acres): 13 200 houses, 87 churches, 44 livery halls, six prisons, four bridges, the Customs House, Guildhall and Exchange were destroyed, as were goods estimated at £3.2 million.⁹ On his next visit to the site, Evelyn describes, in shocked tones, how the searing heat had cracked Inigo Jones's marble facade, and 'that beautiful portico now rent in pieces, flakes of vast stone split in sunder, and nothing remaining entire but the inscription in the architrave which shewing by whom it was built, had not one letter of it defaced'. 'Thus lay in ashes that most venerable church.'¹⁰

Traditionally, architectural history, according to its own conventions, describes the challenge Christopher Wren faced when asked to design the post-fire St Paul's in terms of the relationship between the considerable number of surviving drawings and the classical strictures of Vitruvius, or between the building Wren eventually executed and



Figure 3. Wyck's drawing of St Paul's ruins. (© Guildhall Library, Corporation of London.)

contemporary French basilica which he had visited (in 1665) and admired. Here, however, is material to suggest not only that Wren's intellectual and emotional involvement with the building pre-dated the fire, but also that his pre-fire interest was related to another set of activities in which he and Hooke were engaged together, in which, indeed, they had a larger intellectual (and, I would suggest, emotional) stake at the time than in either surveying or designing buildings—the experimental science of the early Royal Society. At precisely the same time that Hooke was conducting his experiments up Old St Paul's and Wren was attending to the fabric of the building, the two men were together engaged in producing the engravings of minute objects magnified by the new microscope, for Hooke's *Micrographia*.¹¹

The overlapping and interlaced connections between the two men and their sets of activities continued.¹² By 1670, when Wren was made London's Chief Surveyor by Charles II himself, and put in charge of the major rebuilding effort necessitated by the Great Fire, Hooke was working for him on a regular basis for a basic salary of £50 per annum, and—in addition to his surveying—was acting in what architects today would consider an engineering capacity.¹³ Hooke was in any case part of the complementary team appointed for the project at the same time by the Corporation of the City of London (strictly, the client). Thus Wren was London's leading architect and planner, while Hooke was the leading surveyor and engineer acting on behalf of the client. On 12 November 1673, Wren was appointed by Royal Warrant as architect of the new St Paul's. Two years and three designs later, building actually began, in the summer of 1675.¹⁴

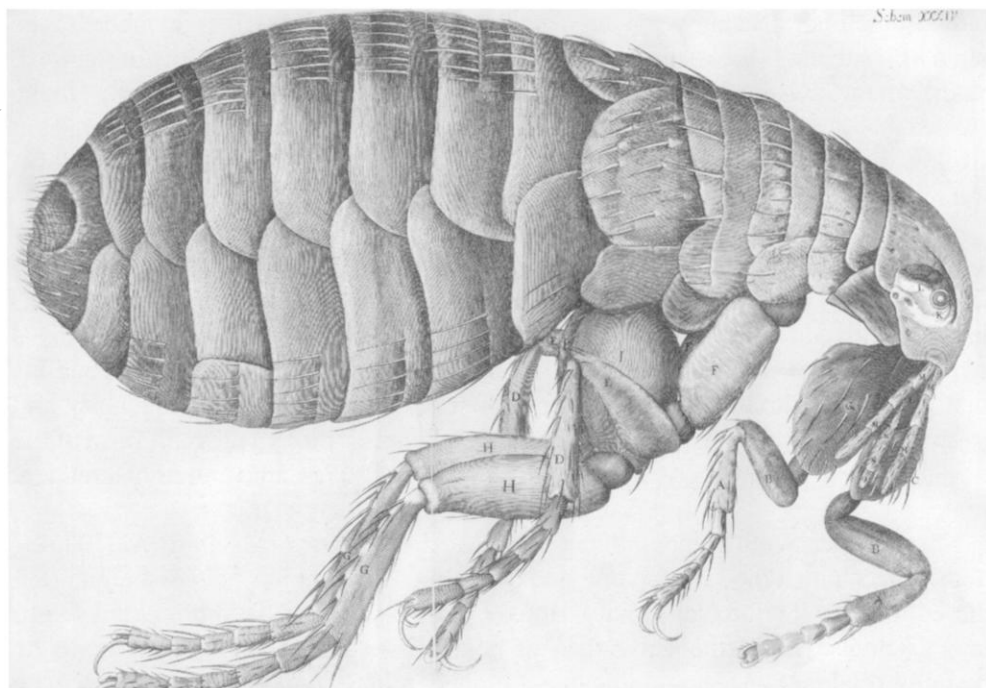


Figure 4. Flea engraving from Hooke's *Micrographia*. (© The Royal Society.)

A horizon-dominating, spectacular St Paul's rising phoenix-like from its own ashes was, in propaganda terms, absolutely central to London's rebuilding effort, and closely associated with the similarly phoenix-like revival of the Stuart monarchy.¹⁵ In fact, that story has become so firmly established, that it comes as a shock to be reminded in a contemporary account that substantial portions of Old St Paul's were still standing after the fire, and that large quantities of manpower and explosives were required to bring down the old cathedral before rebuilding could begin:

The pulling down the Walls, being about 80 Feet high, and 5 Feet thick, was a great and troublesome Work; the Men stood above, and work'd them down with Pickaxes, whilst Labourers below moved away the Materials that fell, and dispersed them into Heaps: the want of Room made this Way slow, and dangerous, and some Men lost their Lives; the Heaps / grew steep and large; and yet this was to be done before the Masons could begin to lay the Foundations.¹⁶

St Paul's-related work occupied a significant portion of the Wren architectural office's time from the late 1660s (that is, even before he officially succeeded Sir John Denham as Chief Surveyor) until the building was eventually completed in 1710/11. (In 1667/68, these activities focused on a final attempt to hang a recladding or refurbishment off the remaining structure, then from the early 1670s attention turned to demolition and complete rebuilding.)¹⁷

Robert Hooke was closely involved with the St Paul's project throughout. Between August 1672 and December 1680 alone¹⁸ there are more than a hundred entries in Hooke's diary indicating visits to the St Paul's site, sometimes accompanied by

Wren, sometimes missing Wren but meeting one or more of the other members of the Wren office there.¹⁹ Hooke instructed bricklayers; he discussed the quality of marble.²⁰ Later, when advising Lord Conway, for whom he designed Ragley Hall, Hooke warned that the mortar and brickwork should be completed well before winter set in to allow the mortar to dry thoroughly, otherwise it would only have to be taken down and rebuilt, 'As I have found in the building of St Pauls.'²¹

It might not, on the face of it, seem surprising that Hooke is rarely part of any celebratory historical account of the magnificent, redesigned St Paul's Cathedral. After all, even today, when major projects are so evidently the product of multidisciplinary teams, architectural critics insist on accrediting buildings to single authors. Hooke's involvement with Wren's architectural masterpiece, however, went well beyond his dual role as site architect and Corporation surveyor. His technical ingenuity and grasp on applied mathematics made a significant contribution to the built form of the most distinctive and uniquely engineered feature of St Paul's Cathedral: its magnificent dome.

Shortly after Wren's appointment to the post of Surveyor of the Royal Works, Hooke made him a model of an inverted dome out of chain links held in their natural curved form by the force of gravity. Hooke added weights and additional links until he had achieved an aesthetically pleasing bell-like shape.²² In engineering mode, he then proposed that one should imagine it dipped in plaster and inverted. The tensile forces would now, he contended, reverse into pure compressions, whose distribution would perfectly simulate those of a completed masonry-constructed dome, with applied loads in the positions where previously there had been hanging weights. The imaginative move here is that of translating pure geometry into statics—in practical terms, transforming the idea on the page into built form.

Hooke alerted The Royal Society to his insight about arch construction several times in late 1670. Together, he and Wren made a verbal presentation at a Royal Society meeting on 19 January 1671. On 7 December 1671, Hooke 'produced the representation of the figure of the arch of a cupola for the sustaining such and such determinate weights, and found it to be a cubico-paraboloid conoid;²³ adding that by this figure might be determined all the difficulties in architecture about arches and buttments.'²⁴ On Saturday 5 June 1675, Hooke records in his diary: 'At Sir Chr[istopher] Wren. At Mr. Boyles. At Mr. Mountacues with Fitch. ... Told Montacue of Pillers 20 foot high for £10 [altogether]. Told Sir Ch[ristopher] Wren of it. He promised Fitch at Paules. He was making up of my principle about arches and altered his module by it.'

Hooke recorded his rationale for such a masonry dome shape, based on the imagined inversion of a hanging catenary, in an anagram inserted at the end of the 1676 printed version of his 1674 Cutlerian lectures ('To fill the vacancy of the ensuing page I have here added a decimate of the centesme of the Inventions I intend to publish, though possibly not in the same order, but as I can get opportunity and leasure...'). Decoded the formula ran: 'As it hangs in a continuous flexible form, so it will stand contiguously rigid when inverted' ['ut pendet continuum flexile, sic stabit contiguum rigidum inversum'].²⁵

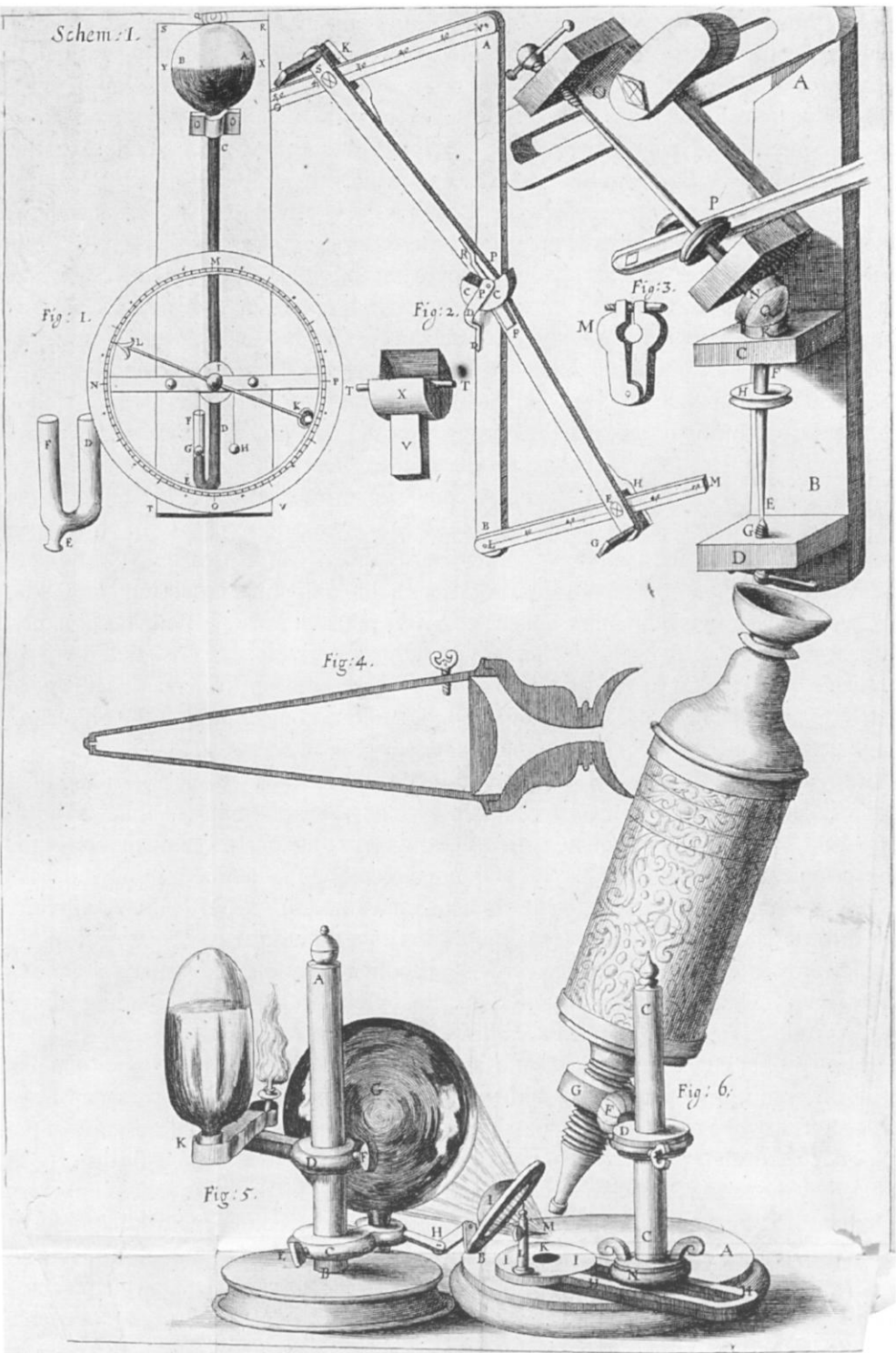


Figure 5. *Micrographia* plate, showing lighting arrangements. (© The Royal Society.)

So, those attractive volumes of measured drawings of (new) St Paul's Cathedral, published just before the Second World War by the Wren Society, with their accompanying seductive arguments about golden sections, the relationship between the dimensions of the cathedral, classical architectural theory and Wren's brilliance as a geometer, tell only a part of the story.²⁶ It is true that the surviving written evidence of the St Paul's project seems to put beauty and geometrical proportion in the foreground. Wren himself wrote, 'Beauty is a Harmony of Objects, begetting Pleasure by the Eye ... always the true Test is natural or geometrical Beauty'.²⁷ But here we are detecting, in texts not customarily linked to the creative process by which the final design for St Paul's emerged, the way in which a significant structural problem is raised by Wren's ambitious concept for the St Paul's elevation as part of a debate elsewhere concerning the stability of structures—and its solution is arrived at in applied mathematical terms, in close collaboration with Hooke.²⁸

Hooke's solution to the technical problem posed by Wren's ambitious design for the dome of St Paul's showed considerable engineering flair (engineer and ingenuity, of course, have the same root). The inner 'cone' supports a formidable load, in the form of the lantern, which raises the dome as high as possible above the London skyline. The cone transmits the load down to the massive piers of the crossing. The cone in its turn provides the firm support for the timber holding up the less substantial exterior dome. The ingenious buttressing, concealed by the peristyle, ensures both the structural and aesthetic integrity of the whole.²⁹

Once we are alert to the dialogue going on here between 'science' (The Royal Society) and 'art' (architectural aesthetics), the unique construction of the built form of St Paul's dome shows evidence of a further connection between Hooke and Wren's more conventionally Royal Society-style scientific activities (to our mind) and their engineering. The cone, which supports the lantern, has a small 'oculus' or light-admitting aperture at its flattened apex. Below this is the perfect hemisphere of the inner dome, with a considerably larger oculus (recalling the Pantheon, and which the observer standing far below on the floor of the cathedral sees as he looks directly upwards). The larger aperture makes us believe that light is flooding directly downwards into St Paul's. In fact, this is an optical illusion: the structural cone is pierced with windows at regular intervals; the outer, insubstantial, 'cladding' dome admits light via gaps all along its scalloped edge, where it meets the lantern. Thus additional light enters the lower oculus indirectly, not directly via the upper oculus.

As a solution to a problem with light, this arrangement closely resembles a contemporary one reached by Hooke in microscopy. In a two-lens microscope of the period it had been found necessary to stop down the upper lens to reduce the distortions caused by the coloured fringes of chromatic aberration. The resulting loss of light was compensated for by indirect side-illumination using a piece of scientific equipment Hooke invented and marketed—his 'scotoscope', a picture of which appears in *Micrographia* alongside his two-lens microscope. To the observer with his microscope, the reduced aperture does not alter the illusion that light is filling the eye-piece lens, as long as there is further ambient light available.³⁰

This last observation advances my argument one step further. Not only do we miss



Figure 6. St Paul's oculus. (© Angelo Hornak Library.)

Hooke's crucial engineering input into new St Paul's if we separate history of science from architectural history, we may also overlook an obvious practical link between building and experimenting—including small- and large-scale work with optical devices. Wren and Hooke, both enthusiastic astronomical observers, both active members of The Royal Society closely involved with the technical side of telescope-building, astronomical observation, microscopes and barometers, with a whole range of associated experiments, naturally regarded the large man-made monuments they were involved in building as linked projects, offering tremendous possibilities as purpose-built 'heights' for practical scientific activities.³¹

Wren's pre-fire proposed recladding of Old St Paul's and his 'warrant' (approved by King Charles) design for St Paul's Cathedral both incorporate vertical shafts within a spire, accessible via a circular staircase, leaving a central vertical drop and allowing for access, ascent and experimental result-taking at various levels. In the case of the Old St Paul's design, the open-work 'pineapple' on the top of the spire might have allowed for use as a zenith telescope—at any rate, during the lengthy period when

it was under construction.³²

The Great Fire which gutted Old St Paul's destroyed one of Hooke's carefully chosen locations for pendulum and barometer experiments. But it did not destroy his commitment to the view that buildings on a grand scale could be conceived of as multipurpose—part monumental building, part scientific instrument or oversized piece of scientific equipment. If we look with a 17th-century scientist's eye at other post-fire buildings, we can begin to recognize designs with the possibility of such a double function in mind.

Among the many London building projects on which the two men worked together was the Monument to the Great Fire itself. It is now generally agreed that it was Hooke's design for the Monument which was finally built (his diary records his putting the finishing touches to the scale model for the 'Pillar' in October 1673, and a final drawing in his hand is endorsed by Wren). According to a contemporary report, Wren and Hooke chose the form for the 200-foot high Monument—a hollow pillar—in the hope that it would be possible to mount an immense zenith telescope inside, to attempt to observe stellar parallax (like the 'tubeless' telescope Hooke had already constructed through his house at Gresham College, which proved not to be stable enough for reliable measurements). The Monument too proved unsuitable, because of expansion and contraction of the brickwork at different temperatures, and because it swayed in the wind—imperceptibly, but too much for the delicate measurements needed.³³

For the stellar parallax experiment, a selected fixed star had to be observed in the same night sky position, precisely six months apart, and any minute displacement in its position recorded. Errors introduced by altered conditions in the observing equipment (caused by meteorological factors, etc.) made detection of such hypothesized small alterations impossible. The Monument did, however, prove a suitable location for more modest kinds of experiments. On 16 May 1678 Hooke recorded in his diary: 'At Fish Street pillar [Monument] tried mercury barometer experiment. It descended at the top about 1/3 of an inch'.³⁴ On 23 May he 'directed experiment at Column. Lent Mr. Hunt a cylinder to do it'.³⁵ The proceedings of The Royal Society for 30 May record that Hooke measured the pressure at various stages as he came down the Monument's steps, but that he was not entirely happy with the accuracy of his equipment: 'he had observed the quicksilver to ascend by degrees, as near as he could perceive, proportional to the spaces descended in going down from the top of the column to the bottom: but because the said stations of the mercury were different from one another but very little, and so it was not easy to determine the certain proportions of the one to the other; therefore he proposed against the next meeting an experiment be tried at the same place with an instrument which would determine that distance an hundred times more exactly: which instrument also he there produced, in order to explain the manner thereof, it being made upon the same principle with the wheel barometer, but more curiously wrought'.³⁶

In December 1678, Hooke measured the height of the Monument—presumably the distance from the upper platform (beneath the crowning burst of gilded flames) to the interior foot of the staircase.³⁷ This would be the distance over which measurements

could be taken for his resumed Torricellian and pendulum experiments—the series he had begun 12 years earlier at the top and bottom of Old St Paul’s tower. The inscription on the Monument’s base explains, of course, that its height was calculated to have symbolic significance—202 feet, the inscription on the base of the column tells posterity, was the distance from it to the baker’s shop where the Great Fire had started. This fact need not distract us, however, from our present interests. In the rebuilding master plan, Wren and Hooke could choose the distance from the supposed origin of the fire. The height of the Monument satisfies Hooke’s scientific requirements for as tall a tower as was consistent structurally with his classic column design. The final height conveniently matches, as closely as one could reasonably ask of such a structure, the height to the cross-beams of old St Paul’s, where Hooke had previously been conducting his barometer and pendulum experiments (it was only after completion that Hooke could reliably measure the height as built, to discover that it was within two feet of his previously measured ‘height’ in the old cathedral).³⁸ Hooke’s Monument was a memorial to the devastation of the Great Fire; it was also a triumphant monument to London’s curious intellects, and that mental moment and ferment of investigative activity in London at the time.

Wren, too, saw the attraction of designing expensive, large-scale public buildings so that they doubled as scientific instruments—specifically, given his own particular interests, as astronomical instruments. Several of the buildings designed collaboratively with Hooke for scientific purposes incorporate bricks and mortar structural features to facilitate astronomical observation. The Royal Observatory Building at Greenwich was the only such building actually realized (and even so, the haste with which Sir Jonas Moore insisted on its being completed prevented their incorporating a purpose-built meridian-line wall—a feature successive Astronomers Royal considered essential). The 1667/68 plans for a proposed newbuild home for The Royal Society in the grounds of Arundel House (never actually executed) included a



Figure 7. The Monument to the Great Fire by Hooke/Wren. (Photograph taken by Edwin Smith, and reproduced by permission of Mrs Olive Smith.)

‘passage gallery’ running the whole length of the attic storey, which was designated ‘for tryal of glasses & other experiments that require length’.³⁹

In February 1704 (the year following Hooke’s death), Wren proposed using the massive, still incomplete structure of St Paul’s Cathedral itself as a super-sized zenith telescope.⁴⁰ Constantijn Huygens (the virtuoso scientist Christiaan’s elder brother) had given The Royal Society the lenses of a 123-foot telescope in 1692 ‘with the Apparatus for using them without a Tube’. Wren’s plan was to mount the telescope in the south-west tower of St Paul’s. As built, that tower includes a structurally spectacular spiral staircase built against the outer wall; the staircase leads up to the library and, as in the case of the Monument, leaves a clear central void for other purposes.⁴¹ James Hodgson, who on Wren’s recommendation had been employed and trained by Flamsteed at the Royal Observatory (where zenith observations had also been attempted), was to have made the observations.⁴² Again the plan failed: the focal length of Huygens’s telescope (as determined by the lenses) was, in fact, too long.⁴³

We have, then, two talented individuals—Hooke and Wren—both with expertise in more than one area of creative ingenuity, unselfconsciously collaborating across a range of projects and nonchalantly breaching notional boundaries between ‘architecture’ and ‘astronomy’, ‘art’ and ‘science’.⁴⁴ Some of their experimental instruments are on a small scale, some monumental.

We may not immediately recognize the similarity between the tower telescope, which formed part of a collaboration between Wren and Hooke, and the famous Boyle pneumatic engine or air-pump, on which Hooke also collaborated (which he alone could make work), but it is there. Both the story of the pursuit of mega-locations to allow precision astronomical observing, and the story of the structural engineering interventions of a practising mechanist in revived classicizing architecture seem highly relevant to the discipline-specific ‘histories’ in which Hooke and Wren figure. At the same time, to separate them into discrete disciplinary boxes threatens to deprive both stories of much of their lasting explanatory force.⁴⁵

The hot-shot scientific and technological collaboration between Christopher Wren and Robert Hooke was, we have begun to discover, an important force, shaping and influencing the ambitious architectural project for rebuilding London after the Great Fire of 1666 and, in particular, guiding the design and execution of the new St Paul’s Cathedral. Here we are beginning to uncover an underlying seamless fabric of inventiveness which (like the massive masonry cone at St Paul’s) supports the awesome visible structures of both the scientific revolution and London’s architectural skyline.⁴⁶

I offer this paper as an encouragement to others excavating the ground between so-called ‘art’ and ‘science’ at the dawn of the modern era. If, I argue, we were to adopt as customary the habit of looking at intellectual and artistic innovation as a unified project, undertaken by cooperating teams of ingenious practitioners (rather than isolated, individual men of genius), who knows how different the intellectual history of the 17th century as a whole might look? If, as historians, we were to share our carefully devised methodologies, to recognize how much the history of science, history of art and architecture, and more generalized cultural and intellectual history have in common (rather than treating them as bounded disciplines with distinct restrictive practices and

modes of approach defined by the club rules of their professional enclaves), how much more we might learn about our own intellectual origins.

I cannot resist one final coda to this tale of accidents of history, grand architectural projects and even grander scientific designs....

In late summer 1665, a devastating outbreak of plague in London forced the members of The Royal Society to disperse hurriedly to the country (economic activity in London was brought to a standstill for almost six months). Boyle and Moray retired to Oxford; Hooke and Wilkins went to Durdans, near Epsom, the seat of Lord Berkeley, taking a quantity of scientific instruments with them, including Boyle's air-pump, so that they could continue working.⁴⁷

Shortly after their arrival, John Evelyn, a frequent visitor at Durdans, found them hard at work, 'contriving Chariotts, new riggs for shippes, a Wheele for one to run races in, & other mechanical inventions'. He wrote admiringly that nothing approaching the investigating power of this little group was to be found elsewhere in Europe, 'for parts and ingenuity'. They had set themselves an ambitious programme of experiments to carry out during their country recess: 'divers experiments of heat and cold, of gravity and levity, of condensation and rarefaction, of pressure, of pendulous motions and motions of descent; of sound, of respiration, of fire, and burning, of the rising of smoke, of the nature and constitution of the damp, both as to heat and cold, driness and moisture, density and rarity, and the like'.⁴⁸

Away from the elaborate protocol and posturing of London Royal Society meetings, Hooke and Wilkins seem to have spent a particularly fruitful—and enjoyable—time practising science together during this period of enforced vacation. The new carriage they were working on (which Huygens sketched in his notebooks) was designed for speed and manoeuvrability. One can picture them careering around Durdans in a prototype coach, testing it for stability and speed.

These speed trials served a double purpose. Hooke and Wilkins took advantage of the similarity of the carriage's motion to that of a ship, to continue trials of the effects of violent motion on pendulum watches, which they had begun in London that spring. In March, Hooke had been asked by The Royal Society to investigate a patent granted to Christiaan Huygens for a pendulum clock that would keep sufficiently accurate time at sea to be used in calculating longitude. On the 15 March, Hooke reported back to The Royal Society (characteristically) that he was not at all impressed, on the grounds that the clock was unlikely to keep proper time if subjected to violent motions up and down, of the kind experienced at sea:

Mr. Hooke remarked that in his opinion, no certainty could be had from pendulum watches for the longitudes, because, 1. They never hung perpendicular, and consequently the cheeks were false. 2. All kinds of motions upward and downward, (though it should be granted, that the watches hung in an exact perpendicular posture) would alter the vibrations of them. 3. Any lateral motion would produce yet a greater alteration.

Lord Brouncker, in his double role as President of The Royal Society and Assistant Comptroller to the Navy Board, ordered that the watches under trial should be brought ashore and the tests continued, as a matter of urgency, in rapidly moving carriages: 'some further experiments should be made with them, by contriving up and down

motions, and lateral ones, to see, what alterations they would cause in them’.

At Durdans, Hooke also continued to work on watches with springs, as indeed he had been instructed to do by The Royal Society (it may have been while they were there together that he gave Wilkins an early version of his spring-balance watch as a gift). Like Huygens during the same period, Hooke also worked on methods and instruments for finding local time at sea (the crucial calculation needed alongside the time at home ‘held’ by the longitude timekeeper). To this end he devised a reflecting quadrant (of a kind eventually brought into regular use in the 1730s) for finding distances by triangulation (fixing places by intersecting rays). He and Wilkins tested the quadrant using that old favourite experimental site of Hooke’s—Old St Paul’s. Hooke reported to Boyle in Oxford on 15 August 1665:

My quadrant does to admiration for taking angles, so that thereby we are able from hence to tell the true distance between Paul’s and any other church or steeple in the city, that is here visible, within the quantity of twelve foot, which is more than is possible to be done by the most accurate instrument, or the most exact way of measuring distances.⁴⁹

Hooke’s design for his important new quadrant survives as a single drawing, without accompanying explanation, found on a loose sheet of paper by Waller after Hooke’s death.

Hooke was scheduled to present his ‘new perspective for taking angles by reflection’ to The Royal Society on 12 September 1666—the week immediately following the Great Fire of London. That meeting did not, of course, take place.⁵⁰

Hooke’s lost quadrant may stand here for the way in which the vagaries and accidents of history shape our understanding of the past, and colour our attitudes. In 1683, Hooke lectured at Gresham College on navigation; one of the scientific instruments he described as invaluable for assisting in finding longitude at sea was a double telescope designed by Wren. Editing Hooke’s posthumous works in 1704, Waller chose to place his account of Hooke’s quadrant alongside Hooke’s own meticulous description of Wren’s telescope, and to include the two devices side by side on the accompanying engraving.⁵¹ Had the Great Fire not occurred, might Hooke and Wren have become a great innovating team in the technology of navigation? Might the longitude problem have been solved by the two of them—Hooke’s balance-spring watch and quadrant, combined with Wren’s telescope? These are, of course, wild, far-fetched ideas.

NOTES

- 1 Birch, *History of the Royal Society* 1, 466 (R. Boyle, *Works*, vol. 5, p. 534).
- 2 *Ibid.* (R. Boyle, *Works*, vol. 5, p. 534).
- 3 Birch, *op. cit.*, note 1, p. 471.
- 4 See Birch, *op. cit.*, note 1, p. 456 for the instruction to Hooke.
- 5 In fact, Old St Paul’s was such a familiar ‘height’ that it was regularly used for experiments requiring results at different elevations (more convenient than climbing a mountain). Bacon, too, conducted experiments up Old St Paul’s. See J. Spedding, R.L. Ellis, and D.D. Heath, *Works of Francis Bacon*, 7 vols (London, Longmans *et al.* 1857–59, vol. 5, p. 405).
- 6 F. Willmoth, *Sir Jonas Moore: practical mathematics and Restoration science*, p. 143 (Woodbridge Boydell Press, 1993).

- 7 H.F. Hutchinson, *Sir Christopher Wren: a biography* (London, Gollancz 1976).
- 8 G. de la Bédoyère (ed.), *The diary of John Evelyn*, p. 171 (Bangor, Headstart History, 1994). After the fire, Pratt wrote to Wren confirming the pre-fire survey for the record. He agreed with Wren that the outward lean of the structural walls was the result of Inigo Jones's not having correctly calculated the effect of hanging the weight of the facing marble from the existing walls. In Pratt's view, the building would eventually have collapsed—worth noting, in view of Inigo Jones's post-Restoration hagiography.
- 9 Willmoth, *op. cit.*, note 6, p. 63; D.L. Smith, *History of the modern British Isles*, p. 217 (Oxford, Blackwell, 1998). The statistics are taken from the inscription on the base of the Monument.
- 10 de la Bédoyère, *op. cit.*, note 8, pp. 173–174.
- 11 Although there is some doubt as to Wren's involvement in the final engravings, we do know that he produced images of a much-magnified flea and louse for the amusement of Charles II, and that he then passed the project to Hooke for completion as a book-length endeavour. I suggest that the engraving of a dissected brain for Willis's *Anatomy of the Brain* (acknowledged by Willis in the text to be by Wren), and the flea engraving from *Micrographia* (see figure 4) are by the same hand.
- 12 Two further connections between The Royal Society and St Paul's which there is not space to discuss here. Hooke thanks Sir John Cutler (sponsor of the Cutlerian lectures) for his generosity, in the preface to *Micrographia*: for 'his honorable Subscriptions for the rebuilding of St. Paul's [pre-fire]' (*Micrographia*, fol. g^v). On 18 September 1666, Henry Oldenburg, Secretary to The Royal Society, wrote to Robert Boyle in Oxford as follows: 'Dr Wren has, since my last, drawn a model for a new city, and presented it to the king, who produced it himself before his council, and manifested much approbation of it. I was yesterday morning with the doctor, and saw the model; which methinks, does so well provide for security, conveniency, and beauty, that I can see nothing wanting as to those three main articles; but whether it has consulted with the populousness of a great city, and whether reason of state would have that consulted with, is a query to me. I then told the doctor, that if I had had an opportunity to speak with him sooner, I should have suggested to him, that such a model, contrived by him, and received and approved by the Royal Society, or a committee thereof, before it had come to the view of his majesty, would have given the Society a name, and made it popular, and availed not a little to silence those who ask continually, what have they done? He answered, that he had been so pressed to hasten it, before other designs came in, that he could not possible consult the Society about it. However, since it is done without taking in the Society, it must suffice, that it is a member thereof that hath done it, and by what I see, hath done it so, that other models will not equal it; and I hope, that when it comes to be presented to the parliament, as the author will be named, so his relation to the Society will not be omitted.' (Birch, *op. cit.*, note 1, *Boyle Works*, vol. 6, p. 230.)
- 13 Hooke's papers for the post-fire survey of the City of London are held at the Guildhall Library.
- 14 *Sir Christopher Wren: an exhibition selected by Kerry Downes*, p. 72 (London, Trefoil Books, for Whitechapel Art Gallery, 1982).
- 15 In fact, a complete redesign of the City of London was part of the Restoration's grand design for a 'fresh start'. It is clear that the designs for a new City (by Wren and Evelyn), which they showed the King within days of the Fire of London, were schemes they had already been working on as part of the 'Restoration'. See *Parentalia*, p. 267: 'Some intelligent persons ... thought it highly requisite, the City in the Restoration should rise with that Beauty, by the Straightness and Regularity of Buildings, and Convenience for Commerce, by the well disposing of Streets and publick Places, and the Opening of Wharfs, &c. which the excellent Situation, Wealth and Grandeur of the Metropolis of England did justly deserve'.
- 16 *Parentalia: or, Memoirs of the Family of the Wrens; viz. Of Mathew Bishop of Ely, Christopher Dean of Windsor, &c. but chiefly of Sir Christopher Wren, Late Surveyor-General of the Royal Buildings, President of the Royal Society, &c.*, p. 283 (London, T.

- Osborn and R. Dodsley, 1750; reprinted Gregg Press, 1965) CML 250 [LS]. An attempt was made by Wren at rebuilding the existing St Paul's, before a masonry collapse caused the abandonment of the project. In 1997 more than 70 carved stones from Inigo Jones's marble portico were discovered during excavations by John Schofield of the Museum of London. They had been reused by Wren for the foundations to his own Cathedral. See <http://www.archaeology.org/9703/newsbriefs/st.pauls.html>.
- 17 See the very clear account of these stages in *Parentalia*.
 - 18 This is the period covered by the first Hooke diary. See H.W. Robinson and W. Adams (eds), *The diary of Robert Hooke MA MS FRS 1672–1680* (London, Taylor and Francis, 1935).
 - 19 These visits and this on-site involvement continue in the later diary, printed in R.T. Gunther, *Early science in Oxford*, p. 10 (Oxford, 'Printed for the Author', 1930).
 - 20 M. 'Espinasse, *Robert Hooke*, p. 104 (London, Heinemann, 1956).
 - 21 E.T. Drake, *Restless genius: Robert Hooke and his earthly thoughts*, p. 131 (Oxford University Press, 1996).
 - 22 Only Drake has the information about the hanging weights, as far as I can see. I assume she gets this from her cited engineering source, E.C. Hambly, 'Robert Hooke, the City's Leonardo', *City University* 2, 5–10 (1987). Since this is precisely the inverse of Christiaan Huygens's proof of the form of a hanging chain in his juvenile work 'De catena pendente' (1646), this is worth checking out. On Huygens's catenary, and the subsequent discussions with Jakob Bernoulli, see J.G. Yoder, *Unrolling time: Christiaan Huygens and the mathematization of nature*, pp. 108–111 (Cambridge University Press, 1988). Hooke's library contains (unbound) the issue of the *Acta eruditorum* in which Jakob Bernoulli challenged mathematicians to find the true shape of the catenary (June 1690). See A.N.L. Munby (ed.), *Sale catalogues of libraries of eminent persons* (London, Mansell Publishing, 1975).
 - 23 This remark is part of a contemporary discussion about curves of this kind, and is not far off the mark, in 17th-century mathematical terms.
 - 24 Load-bearing arches: 8 December, 15 December, 12 January (Mr Oldenburg mentioned that Dr Wren had also a demonstration of it. It was desired that these demonstrations might be both delivered and opened together by the president), 19 January 1671 (both men presented their versions). 7 December 1671: 'Mr. Hooke produced the representation of the figure of the arch of a cupola for the sustaining such and such determinate weights, and found it to be a cubico-paraboloid conoid; adding that by this figure might be determined all the difficulties in architecture about arches and buttments' (Birch, *op. cit.*, note 1, vol. 2, p. 984). My hunch is that here is the evidence that Hooke had seen the Huygens catenary proof. Huygens shows by the thought experiment of hanging weights on a catenary that it becomes paraboloid only when such weights are added. Hooke inverts the diagram for that proof, and uses it to solve the structural problem of supporting weights on an arch. By the time Wren and Hooke came to the final design for the dome and its supporting catenary cone, after 1702, Bernoulli and others had publicly produced the equation for the pure catenary, which would have allowed the St Paul's inner dome to be properly constructed as such (see Downes, *op. cit.*, note 14, for the late modifications to the configuration of the cone and dome). Even if the masons could only approximate a catenary incorporating the inward-leaning inner peristyle and arch-supported dome above, the intention to follow an inverted hanging chain is still an engineering innovation.
 - 25 *Ibid.* p. 131. The announcement runs: 'The true Mathematical and Mechanichal [sic] form of all manner of Arches for Building, with the true buttment necessary to each of them. A Problem which no Architectonick Writer hath ever yet attempted, much less performed.' (Gunther, *op. cit.*, note 19, vol. 8, p. 151). In his diary for Sunday 26 September 1675, Hooke himself gives this as follows: 'Riddle of arch, of *pendet continuum flexile, sic stabit grund Rigidum*'.

- 26 It remains to be seen whether they are even correct—given the difficulty in assessing the shape of the interior ‘cone’ (as I found myself when I climbed around above the inner dome, and under the outer one). All surveyors of the fabric since the late 18th century assume it is a pure cone. In fact, it appears to be more curved (or at least a succession of cones moving inwards at each prop-point). Clearly more work needs to be done on this.
- 27 The complete quotation, taken from *Parentalia*, *op. cit.*, note 16, runs: ‘There are natural Causes of Beauty. Beauty is a Harmony of Objects, begetting Pleasure by the Eye. There are two Causes of Beauty, natural and customary. Natural is from Geometry, consisting in Uniformity (that is Equality) and Proportion. Customary Beauty is begotten by the Use of our Senses to those Objects which are usually pleasing to us for other Causes, as Familiarity or particular Inclination breeds a Love to Things not in themselves lovely. Here lies the great Occasion of Errors; here is tried the Architect’s Judgment: but always the true Test is natural and geometrical Beauty.’ Cit. J.A. Bennett, *The mathematical science of Christopher Wren*, pp. 3–4, and see chapter 10 *passim* (Cambridge University Press, 1982).
- 28 Anthony Geraghty has now argued that the surviving drawings, collected and printed by the Wren Society, were in any case neither the working drawings (which inevitably perished during the building process), nor in Wren’s hand.
- 29 I am arguing that the cone which supports the lantern attempts to approximate to an inverted catenary. Below it, the perfect hemispherical ceiling with its larger oculus, merely supports its own weight. On the innovative, unconventional cone-shaped support see Hutchinson, *op. cit.*, note 7, p. 133. I am currently engaged in further work to determine whether the built form approximates a catenary, and whether the slope changes at the points at which the external wooden trusses meet it.
- 30 See L. Jardine, *Ingenious pursuits. Building the scientific revolution*, ch. 2 (London, Little, Brown, 1999): ‘In order to make the exquisitely detailed drawings upon which *Micrographia*’s illustrations were based, it turned out that he needed a brighter light-source than sunlight or candlelight to illuminate his specimens, to sharpen the quality of the image seen through his microscope eye-piece. Undaunted, and with characteristic improvisatory flair, Hooke had invented a purpose-built piece of image-enhancing apparatus. He placed a light-condensing brine-filled globe between his lamp light-source and his specimen, then narrowly focused the lamp’s intensified beams by means of a convex lens. By adjusting the relative positions of lamp, globe and lens he found he could improve the magnified image of his subject considerably. He called it his ‘scotoscope’.’ See also R.H. Nuttall, ‘That curious curiosity: the scotoscope’, *Notes Rec. R. Soc. Lond.* 42, 133–138 (1988).
- 31 Wren and Hooke were also friends. See R.G. Frank, *Harvey and the Oxford physiologists: scientific ideas and social interaction*, esp. ch. 3 (Berkeley, University of California Press, 1980).
- 32 It is worth making a preliminary remark here on construction time, and Wren’s alertness to its possibilities as well as its drawbacks. In his pre-fire survey of Old St Paul’s, Wren suggested that the old tower should not be demolished prior to erecting his new cupola: ‘I should not persuade the Tower to be pull’d down at first, but the new Work to be built round it, partly because the Expectation of Persons are to be kept up; for many Unbelievers would bewail the Loss of old *Paul*’s Steeple, and despond if they do not see a hopeful Successor rise in its stead; and chiefly because it would save a great Quantity of scaffolding Poles; the Scaffolds which are needful being fix’d from the old to the new Work; and when the *Tholus* or inward Vault is to be laid, the Tower taken down to that Height will rest the Centers of the Vault with great Convenience, and facilitate the planting of Engines for raising the Stones; and after all is finish’d and settl’d, the Tower that is left may be taken clear away from within’, *Parentalia*, *op. cit.*, note 16, p. 276.
- 33 Bennett, *op. cit.*, note 27, pp. 41–42.
- 34 Robinson and Adams, *op. cit.*, note 18, p. 358.
- 35 Robinson and Adams, *op. cit.*, note 18, p. 359.

- 36 Birch, *History of the Royal Society* 3, 409–410.
- 37 *Ibid.*, p. 388.
- 38 The massive size of the base of the column—which contains the lengthy inscription about the circumstances and consequences of the fire—makes clear the fact that the column’s height is intended to be as imposing (and as great an engineering and building feat) as possible.
- 39 A.D.C. Simpson, ‘Robert Hooke and practical optics’, in M. Hunter & S. Schatter (eds), *Robert Hooke: new studies*, pp. 39–41 (Woodbridge, Boydell Press, 1989).
- 40 Royal Society MS Council Minutes 2 (copy), p. 169; cit. Bennett, *op. cit.*, note 27, p. 42.
- 41 The spiral staircase, designed by William Kempster, is justifiably regarded as one of the marvels of St Paul’s, singled out in guidebooks. See, for example, V. Hart, *St Paul’s Cathedral: Sir Christopher Wren* (London, Phaidon Press, 1995).
- 42 James Hodgson (1672–1755) was Master of the Royal Mathematical School at Christ-Hospital in London, and was a Fellow of The Royal Society. In addition to mathematics, he wrote books on navigation, chronology, annuities and astronomy.
- 43 Bennett, *op. cit.*, note 27, p. 42.
- 44 We may also note a Bacon connection here, which takes us back to my opening remarks, and the suggestion that Bacon was indeed a ground-breaker with respect to monumental instruments, as elsewhere in the new science. In the *New Atlantis* one of the Fathers of Salomon’s House describes how among their advanced scientific resources they have ‘high towers; the highest about half a mile in height; and some of them likewise set upon high mountains; and that the vantage of the hill with the tower is in the highest of them three miles at least’. These towers are used ‘according to their several heights and situations, for insolation, refrigeration, conservation; and for the view of divers meteors; as winds, rain, snow, hail; and some of the fiery meteors also. And upon them, in some places, are dwellings of hermits, whom we visit sometimes, and instruct what to observe’ (Spedding, Ellis and Heath, *op. cit.*, note 5, vol. 3, p.157).
- 45 There is one further cross-connection between the St Paul’s rebuilding and The Royal Society’s science. Some items in Sir Hans Sloane’s collection of antiquities are labelled as having been found during the excavations for the post-fire rebuilding, specifically, at least one from St Paul’s. See A. MacGregor (ed.), *Sir Hans Sloane: collector, scientist, antiquary, founding father of the British Museum* (London, British Museum Press, 1994).
- 46 Inevitably, others are at this very moment building bridges between art and science, architecture and engineering in the 17th century. See, for example, James Campbell, ‘Architect as engineer: Sir Christopher Wren, the Royal Society and structural carpentry in the late seventeenth century’, Gresham College lecture, 23 October 2000, and Campbell’s doctoral thesis, ‘Sir Christopher Wren, the Royal Society and the development of structural carpentry 1660–1710’ (University of Cambridge, 1999). See also the work of Anthony Geraghty on Wren’s churches.
- 47 Letter from Hooke to Boyle, August 1665, in Gunther, *op. cit.*, note 19, vol. 6, p. 250. Wilkins had been chaplain to Lord George Berkeley in the early 1640s.
- 48 B. Shapiro, *John Wilkins, 1614–1672: an intellectual biography*, pp. 199–200 (Berkeley, University of California Press, 1969).
- 49 Gunther, *op. cit.*, note 19, vol. 6, pp. 249–250.
- 50 Andrewes fails to notice the significance of the date on which (according to the manuscript) Hooke’s device was to have been shown to The Royal Society, so surmises that there was little interest in it (rather than that, in the event, no-one saw it). See W.J.H. Andrewes, ‘Finding local time’ in Andrews (ed.), *The quest for longitude*, p. 401 (Cambridge, MA, Harvard University, 1996).
- 51 See Andrewes, ‘Finding local time’, 401. For the two drawings together see R. Waller, *The Posthumous Works of Robert Hooke*, table 11 (London, 1705).