Dean Hawkes

The Origins of Building Science in the Architecture of Renaissance England

In the twenty–first century, *building science* is a firmly established concept and plays an important role in both the practice of architecture and architectural education. In its modern definition, the origins of building science can be traced back to the nineteenth century. In the wake of the industrial revolution, it developed hand–in–hand with the new technologies of building: structure, construction, and heating and ventilation.[1] Joseph Gwilt's, Encyclopaedia of Architecture (Gwilt 1825) was a major reference work for British practice.[2] The book is in four parts:

Book I, History of Architecture
Book II, Theory of Architecture
Book III, Practice of Architecture
Book IV, Valuation of Property

It is in "Book II, Theory of Architecture" that we find the technical/scientific content, chapters discussing:

Mathematics and Mechanics of Construction
Materials used in Building
Use of Materials or Practical Building – this includes extensive sections on 'Ventilation' and 'Warming.'

In the twentieth century, building science advanced and became institutionalized with the creation of organizations such as the Building Research Station (BRS) in Britain and the Reichsforschungsgesellschaft für Wirtschaftlichkeit im Bau–und Wohnungswesen (RFG) in Germany.[3] Although the relationship between building science and the practice and theory of architecture in the twentieth century is largely uncharted—and, in many ways, uncertain—elements of science and technology are central to the very nature of modern building.[4]

The relation of architecture and science has, however, a much longer history. This paper examines how architecture was transformed by the emergence of organized science in England in the period between the end of

1 Important texts of particular relevance to the relation of technology and architecture are; Sigfried Giedion, *Mechanization Takes Command: a contribution to anonymous history*, Oxford University Press, Oxford, 1948 and Lewis Mumford, *Technics and Civilization*, Routledge, London, 1934. Reyner Banham's *The Architecture of the Well–tempered Environment*, The Architectural Press, London, 1969, opened up the study of environmental science and technology that has been developed further by the present author and others. See Dean Hawkes, *The Environmental Tradition*, E & F N Spon, London & New York, 1996, *The Environmental Imagination*, Routledge, London & New York, 2008 and *Architecture and Climate*, Routledge, London & New York, 2012.

2 Joseph Gwilt, *An Encyclopaedia of Architecture: Historical, Theoretical and Practical*, Longmans, Brown & Green, London, 1st Edition, 1825. Further editions, 1836, 1867, 1876 and 1888. The book remained in print into the twentieth century.

3 See F.M. Lea, *History of the Building Research Station*, HMSO, London, 1974 and Sigurd Fleckner, Reichsforchungsgesellschaft für Wirtschaftlichkeit in Bau– und Wohnungswesen, 1927–1931, Aachen, 1993 for accounts of institutional building science in Britain and Germany.

4 Modern working definitions of these terms are; Science, noun: the intellectual and practical activity encompassing the systematic study of the structure and behaviour of the physical and natural world through observation and experiment. Technology, noun: the application of scientific knowledge for practical purposes. Oxford English Dictionary, 1998 Edition, 2001 revised edition.

the sixteenth century and the middle years of the eighteenth century. The discussion is principally concerned with the aspect of building design that we now identify as 'environmental' and focuses on three distinct phases in architectural history; the last years of the reign of Queen Elizabeth I, with the remarkable 'prodigy' houses built by Robert Smythson; the second part of the seventeenth century, when Christopher Wren emerged as the dominant figure in English architecture; and the middle years of the eighteenth century when the 'Palladian movement' adapted the sixteenth century architecture of the Veneto to the English condition.

In the history of science this period is defined as the 'early modern era.' The introduction to volume 3 of The Cambridge History of Science characterizes it as a time of

> pell–mell change at every level: the astounding growth in the number of plant species and mathematical curves identified, for example, the creation of whole new ways of conceiving the natural order, such as the idea of "natural law," the deployment of natural philosophers as technical experts on the government payroll and of natural philosophy as the best argument for religion. (Park and Daston (eds.) 2006: 13)

'The Mechanical Arts' of the sixteenth century embraced "practical applications of mathematical knowledge in fields such as architecture, navigation, clockmaking and engineering." (Park and Daston (eds.) 2006: 9). The invention of machines for a myriad of purposes was a great project of this period. J.A. Bennett catalogues innovations in the development of clocks and celestial instruments, mathematical and optical instruments and tools for navigation, surveying, warfare and cartography (Bennett 2006). Many of these were relevant for and, in some instances, derived from architecture. Bennett also points to the important part played in this early science by the particularly architectural skill of drawing. In the seventeenth century the science of meteorology came into being as instruments for measuring weather—atmospheric pressure, air temperature, the velocity and direction of the wind and rainfall—were devised and progressively refined (Knowles Middleton 1969). The foundation of the Royal Society brought a new focus and organization to the development of science in England. This took place on November 28, 1660, at a meeting in Gresham College, London, following a lecture by Christopher Wren, who at the time, was a scientist and Gresham Professor of Astronomy, but was of course, to become the dominant architect of the age. In 1665 the Society established the Philosophical Transactions, which initiated the practice of authoritative publication of scientific work and was soon imitated throughout Europe (Johns 2006). Isaac Newton (1642–1727), the greatest scientist of the day was elected a fellow of the Society in 1672 and became its President in 1701, a position he held until his death in 1727. Under the auspices of the Society and the profound influence of Newton, English science flourished in the eighteenth century and entered into a new relationship with both the theory and practice of architecture.

Architecture and Science: Sixteenth Century

In sixteenth–century England, both architecture and science were quite unlike their modern definition and practice. Writing about the idea of the architect at this period, Mark Girouard suggests that,

> Although both John Shute […] and John Dee […] expounded the Renaissance and Vitruvian ideal of the architect, the concept remained an alien one. The mediaeval system continued with little alteration […]. (Girouard 1983: 7)

In contrast to this, Summerson describes the most significant building organization at the end of the sixteenth century, the Royal Works (Summerson 1969). Located at a permanent building yard in Whitehall, the organization was presided over by the Surveyor, beneath whom was a hierarchy of subordinates who represented and supervised the work of large numbers of tradesmen, carpenters, joiners, masons and other trades. This provided the model by which most large building projects were undertaken and suggests that building practice had moved on from the informal procedures of earlier times.

Robert Smythson was responsible for some of the greatest buildings of Elizabethan England. Girouard surmises that he may have been born in the north of England and that he served an apprenticeship as a mason in London, when he also learned to draw. His memorial in the church at Wollaton describes him as "architector and survayor" (Girouard 1983:168). It is drawing that allows us to identify Smythson as an architect. The Smythson Collection of the Royal Institute of Architects preserves a large number of drawings definitively identified as drawn by Robert Smythson. Other drawings in the collection from the same period, are drawn by Smythson's son, John Smythson and others. (Girouard 1962). Although some of the drawings are of measured surveys of existing buildings, others are clearly drawings made before the construction of buildings and, hence, illustrate the relationship between drawing and building that survives into modern practice. Smythson was in that sense an architect.

There are two great houses that most completely reveal Smythson's genius, Wollaton Hall, Nottingham (1580–1588) and Hardwick Hall, Derbyshire (1590–1597). These are counted among the 'Prodigy Houses,' a group of houses built by ministers and courtiers of Queen Elizabeth (Summerson 1969). Smythson was a near contemporary of Andrea Palladio, their dates being 1534–1614 and 1508–1580 respectively, but their buildings could hardly appear more different. In contrast to the absolute classicism

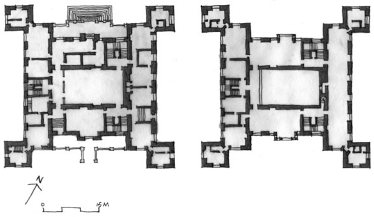


Fig. 1 Robert Smythson, Wollaton Hall, Plans. Author

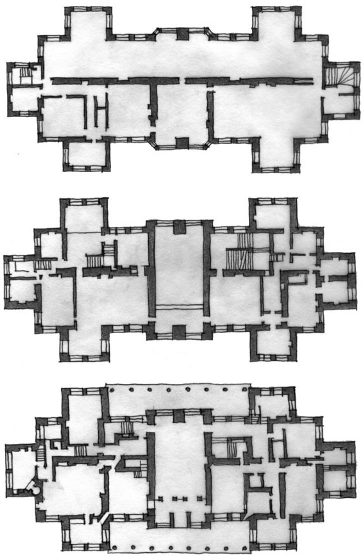


Fig. 2 Robert Smythson, Hardwick Hall, Plans. Author

of Palladio's villas, these English houses barely reveal its influence. Summerson observes, "Classicism made its way in England not as a method of building, but as a mode of decorative design." (Summerson 1969: 51). Wollaton and Hardwick are, in both plan outline and elevation, strongly symmetrical and display classical elements in their details, but they are far from classical. But architecture has other concerns than style. In previous studies I have pointed to the manner in which the designs of Palladio and Smythson evince a deep response to the physical climates within which they are set (Hawkes 1996). In Palladio's case the question of climate is made explicit in I Quattro Libri, where he gives precise prescriptions on how to determine the sizes of windows in relation to the climate of the Veneto and is similarly precise in discussing the design of fireplaces and chimneys (Palladio 1570). The question is whether such a relationship between theory and practice, or science and craft, existed in England. Can Smythson's designs be regarded as scientific?

The plans of Wollaton and Hardwick (fig. 1 & 2) are similar in their bi–axial symmetry. At Wollaton the almost square plan is elaborated with four corner turrets. Hardwick is rectangular with turrets in two groups of three at either end. Each house has a dramatic silhouette that is further emphasized by their hilltop locations (fig. 3 & 4). In the sixteenth century, Europe was in the depths of the so–called 'Little Ice Age' (Fagan 2002), when very low temperatures prevailed throughout most winters. In the English climate the orientation of a building has a great effect on the conditions within. Wollaton is oriented with the cardinal almost on the diagonal of the plan,[5] and at Hardwick, the long axis of the plan lies a fraction from due north–south. These facts allow us to analyze the environmental sophistication of the buildings.

Wollaton is entered from the north–west, and a complex, sheltering route leads to the central great hall. This is lit by high clerestory windows and warmed by two great fireplaces. The central location insulates the space against the cold. Two of the most important rooms are the dining room on the ground floor and the south great chamber immediately above it on the first floor. The dining room was probably the most intensively inhabited space in the house. This was where the women of the household spent most of their time in the winter months and where the entire household would dine.[6] The room has a large fireplace on the inner wall. The south great chamber was the principal ceremonial room, matched by a similar space on the north side. The inventory of the contents of the house, made in 1601, refers to "the southe great chamber alias the best chamber" and lists its lavish furnishings in contrast to the sparse contents of the north chamber.[7] The south–facing windows have larger amounts of glass than the north as a further acknowledgment of the distinction between the different aspects.

Hardwick Hall was built for Elizabeth, Countess of Shrewsbury. She was 70 years old when the house was completed in 1597. The twentieth–century

5 This is also the orientation of Palladio's La Rotonda, Vicenza.

6 This is discussed in Pamela Marshall, *Wollaton Hall: an Archaeological Survey*, Nottingham Civic Society, Nottingham, 1996, and Alice T. Friedman, *House and Household in Elizabethan England: Wollaton Hall and the Willoughby Family*, University of Chicago Press, Chicago, 1989.

7 Inventory in Pamela Marshall, *Wollaton Hall: An Archaeological Survey*, op cit.

English architect, Peter Smithson, wrote as follows:

> In Hardwick Hall there is a gallery that runs along the whole extent of the house. What's nice about (the plan) is that it indicates the thick spine wall, where the fireplaces are [...] and the perimeter windows that let in the light. (Smithson 2005: 62)

This description refers to the second floor of the house, where the relationship between the masonry spine wall and the glassy perimeter is most clearly seen. The tall windows fill the interior with natural light, a necessity in a period when artificial light sources were minimal in quality and number. The inventory of the contents of the house made in 1601, just four years after its completion, tells us that there were two hanging candelabras in the double height great hall on the ground floor, plus four candlesticks fixed to the walls (Boynton (ed.) 1971). Other than these, the inventory lists just 30 single candlesticks that would have been carried around the house. It has been observed that in Shakespeare's day, the difference between day and night was extreme, particularly in the winter months. "In the age of candle and rush–light, nights were seriously dark." (Bate 2007: 365) The house was heated by 28 fireplaces, fueled by timber from the woods and copses on the estate and in some cases by coal from the estate's mines. These fireplaces at the centre of the house warmed the great mass of masonry and compensated for the inevitable cold of the glass perimeter.

Fig. 3 Robert Smythson, Wollaton Hall, Exterior. Author

Fig. 4 Robert Smythson, Hardwick Hall, Exterior. Author

The strict symmetry of the exterior conceals a remarkable freedom in the internal organization of the house. My analysis proposes that this is a specific response to questions of comfort in the harsh climate of the time. It is striking that the principal public and private apartments are all placed at the southern end of the plan. There they benefit from the warmth of the sun as it tracks from east to west. The ground floor houses chambers for senior members of the household, including a nursery for the countess' young grandchildren. Immediately above these are the countess' own rooms, a withdrawing chamber and bedroom and a chamber for her older granddaughter. Here, protected by floors below and above, these relatively small rooms receive the best of the sun, and their open fires easily warm them.[8] On the top floor, the high great chamber occupies the entire south–west corner. This is the principal room of the house and the site of great events. In this time of nighttime darkness, dinner and other ceremonials began in mid–afternoon, to enjoy the daylight that flooded into the room.

It is clear that these buildings represent a deep understanding of the climate of England in their form, planning and materiality. The question is whether this understanding may be regarded as *scientific*? As we saw earlier, architecture had a place within the taxonomy of sixteenth century science as one of the *Mechanical Arts*. To what extent did this status bear upon the conscious practices of a man such as Smythson? Girouard argues that Smythson's designs are fundamentally a continuation of the native

8 The furnishings of these rooms included warm carpets, thick curtains and coverlets, all to supplement the warmth of the open fires. See *The Hardwick Inventory of 1601*, op cit.

Gothic vernacular tradition and thus implicitly lie outside the realm of science (Girouard 1983). But, in my analysis of their response to the English climate, buildings such as Wollaton and Hardwick mark a radical step away from the procedures of the vernacular. At a time when our modern concepts of climate and comfort were unrecognized and beyond numerical description, it may be suggested that Smythson achieved a sophistication and consistency in these buildings that places them within the realm of the science of their time.

Architecture and Science: Seventeenth Century

Christopher Wren (1632–1723) was first a scientist and then an architect, so his education and practice background was quite unlike Robert Smythson's. John Summerson has explored the broad relationship between his science and his architecture. In setting the scene on the relation of science and architecture in the seventeenth century, Summerson writes:

> For us today the problem is bedeviled by those distinctions between "scientific" and "artistic" which were erected during the course of the nineteenth century and which it is exceedingly misleading to attempt to apply to the seventeenth. It is equally bedeviled by the element of rationalism which has crept into our notion of architecture, so that the idea of a "scientist" becoming an "architect" immediately suggests the application of some special rigour of a "functional" kind to design problems. (Summerson 1990: 65)[9]

9 See John Summerson, "The Mind of Wren" in *Heavenly Mansions and Other Essays on Architecture*, Cresset, Press, London, 1949. A later essay is "Christopher Wren: Why Architecture?" in *The Unromantic Castle and Other Essays*, Thames & Hudson, London & New York, 1990. A later study of Wren's science and architecture is, J.A. Bennett, *The Mathematical Sciences of Christopher Wren*, Cambridge University Press, Cambridge, 1982.

Fig. 5 Christopher Wren, Sheldonian Theatre, Exterior. Author

In Summerson's analysis the Sheldonian Theatre at Oxford plays a key part (fig. 5). On April 29, 1663, Wren exhibited a model of the building at a meeting of the Royal Society, an event that, perhaps, suggests the unity of the *scientific* and *artistic*. At the end of the same year, on December 9, Wren presented a design for a 'weather–clock' to the Society (fig. 6). This clockwork device plotted recordings of temperature, barometric pressure, and wind speed and direction (Knowles Middleton 1969). The instrument was inspired by a never realized proposal to construct a History of the Seasons (Wren Junior 1750).[10] Summerson suggests that the 'immature' architecture of the Sheldonian is reminiscent of the "decorative trimmings" (Summerson 1990: 102) of the weather–clock. He contrasts the *artistic* shortcomings of the visible architecture, exterior and interior, with the sophistication of the *scientific* design of the concealed roof trusses that span the wide space below – "a real piece of 'Royal Society' research." (Summerson 1990: 102) But Summerson also insists that the designing of a classical façade and a new kind of roof structure were not, for Wren and his contemporaries, in conflict in any way, "The fact is that to them the natural equivalent of scientific thought in architecture was classical design." (Summerson 1990: 102)

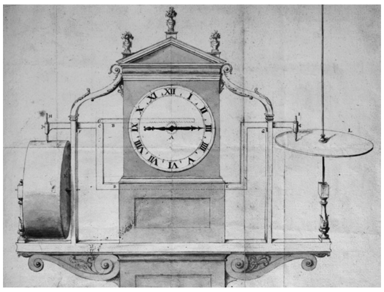


Fig. 6 Christopher Wren, Weather Clock. © The Royal Society

10 The proposal is included in Christopher Wren, Junior, *Parentalia*, the collection of Wren family documents compiled by Wren's son and published in 1750. Reprinted by The Gregg Press, London, 1965.

11 Dean Hawkes, "Christopher Wren and the origins of building science," in *Architecture and Climate*, op cit.

In recent research, the author examined a number of Wren's buildings from an environmental perspective and proposed that they demonstrate a previously unidentified link between his scientific knowledge and his architecture.[11] The Sheldonian Theatre is an ideal example. The building was designed primarily as the location for the annual university degree ceremony, the Encaenia, which is held on the Wednesday of the ninth week of the university's Trinity Term. This is the week of the summer solstice. The building was also used for musical performances and as an anatomy theatre; in addition, it was the home of the university printing press. Nonetheless, the Encaenia was its principal raison d'etre and it was this that most fundamentally influenced the design. The plan (fig. 7) is usually said to derive from the Theatre of Marcellus as illustrated by Vitruvius and Serlio. But a roofed space in seventeenth century England is very different from an open–air theatre in ancient Italy.

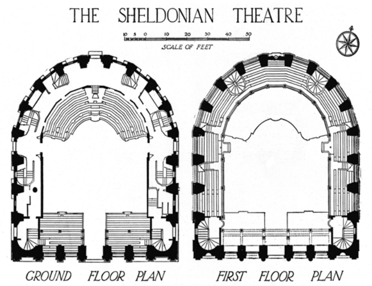


Fig. 7 Christopher Wren, Sheldonian Theatre, Plans.


Fig. 8 Christopher Wren, Sheldonian Theatre, Interior. Author

The Encaenia is a day–long ceremony that takes place before a large audience, all in heavy academical dress. At this time of year there would be ample daylight, but the crowded room would be in danger of becoming very hot. These conditions are directly addressed in the design. The building stands to the north of the already existing Bodlean Library and is entered from the south, through the classical façade—criticized by Summerson. The amphitheatre is illuminated by daylight from great windows, ranging from east through north to west, above and below the gallery (fig. 8). Twentieth century building science has confirmed that under the usually dull and changeable English sky, good light in a building depends on providing an unobstructed view of a good portion of the sky; the sky component of the daylight factor.[12] This is precisely what Wren's fenestration provides. By virtue of the orientation it also reduces the amount of direct sunlight that will enter during the long day. In addition, the arrangement also provided effective and necessary cross ventilation of the building. A contemporary description of the building is given in Robert Plot's, The Natural History of Oxfordshire (Plot 1677). In this, he gives a detailed description of the ingenuity of the design of the windows and their opening mechanisms that provide copious ventilation but prevent the ingress of rain, an important matter in the English climate. Alongside the *light* and *heat* just discussed, the third element of the scientific architectural environment is *sound* (acoustics). These were admired at the opening of the building on July 19, 1669, and celebrated in a Pindaric Ode, In Theatrum Sheldonianum et eius Architectum, that was delivered on the day. This reports that there were no unwanted echoes and that both voices and music were heard with "pleasing purity" (Jardine 2002: 218). Was this a coincidence, or is it further evidence of Wren's *scientific* understanding brought to bear on this aspect of the architecture?

Notwithstanding, his critique of the *artistic* merit of the Sheldonian, Summerson was fulsome in his recognition of the building's place in the unfolding story of the relation of architecture and science in England.

12 R.G. Hopkinson, *Architectural Physics: Daylighting*, HMSO, London, 1963.

> [...] of all buildings (the Sheldonian) most exactly reflects the early image of (the Royal Society) and embodies its philosophy.
> [...] this Theatre is the dispensation of a mode of thought most obviously manifested in the field which we now call science but which can be seen more rarely to have left its imprint on the arts and especially in architecture.
> [...] everything in this building wears the livery of the Experimental Philosophy and of the Society with whose founding members it was so concerned.
> It reflects, like no other I can think of, a crucial phase in our intellectual history – a phase of energy and optimism when the arts and sciences were conceived to be as symmetrically and devotedly disposed about Truth [...] (Summerson 1964: 8)

13 "Letter to a Friend on the Commission for Building Fifty New Churches," in Christopher Wren, Junior, *Parentalia*, op cit. Wren's "Letter" is reproduced in full in Lydia Soo, *Wren's Tracts on Architecture and Other Writing*, Cambridge University Press, Cambridge, 1998. 112-117.

The greatest architectural project of Wren's life, with the exception of the building of St. Paul's cathedral, was the rebuilding of London's churches following the destruction caused by the Great Fire of 1666 (Jeffrey 1996). In 1670 the Rebuilding Act set up Commissioners to direct the reconstruction of churches and Parliament authorized a list of no less than 51 buildings. This began a process that involved Wren for forty years. In 1708 a new act of parliament recommended the construction of a further 50 churches in the city, and Wren, then 76 years old, took the opportunity to set out clear principles for the design of these.[13] The "Letter" contains a set of objective prescriptions on the practical aspects of designing churches for "the new reformed religion" (Wren Junior 1750: 323), that of post–Restoration Anglicanism. In my analysis these are a demonstration of Wren's *scientific* approach to questions of light and sound in this new configuration of space for worship. He proposed that the churches should be for a congregation of two thousand in which

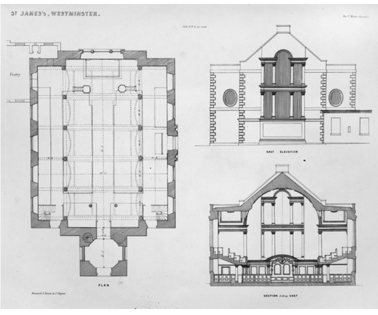


Fig. 9 Christopher Wren, St. James's, Piccadilly, Plans and Sections. J. Clayton (1848)

> all who are present can both hear and see. The Romanists indeed, may build larger churches, it is enough if they hear the Murmur of the Mass, and see the Elevation of the Host, but ours are to be fitted as Auditories. (Wren Junior 1750: 320)

The concern for daylight and acoustics brings exactly the same priorities to the design of sacred space as he applied at the Sheldonian Theatre. Beginning with acoustics he offered a mathematical formula, "Concerning the Placement of the Pulpit:"

> A moderate voice may be heard 50 feet distant before the preacher, 30 feet on each side and 20 behind the pulpit. (Wren Junior 1750: 320)

14 In seventeenth century London the surrounding buildings were lower than most of their modern replacements, but St. James's remains the 'lightbox' that Wren intended.

From this, Wren calculates that a church "should be at least 60 Feet broad and 90 Feet long." (Wren Junior 1750: 321) The entire topography of the building follows from this as sound lines and sight lines are precisely organized. The clearest example of this is St James's church, Piccadilly (1676–1684), which Wren specifically refers to in the "Letter." The plan is a simple rectangle with galleried aisles on either side of a barrel–vaulted nave (fig. 9). This brings the entire congregation to be within good hearing distance of the pulpit, which is placed at the south side of the chancel. The arrangement also provides good sightlines. The same process that was successful at the Sheldonian Theatre works here to address difficulties of daylight under the English sky. Tall windows above the galleries fill the space with light from north and south, with smaller lights below to illuminate the aisles (fig. 10). From all points of the interior, there is a clear view of the sky above the surrounding buildings; once again, in modern terminology, achieving a high sky component of the daylight factor.[14]

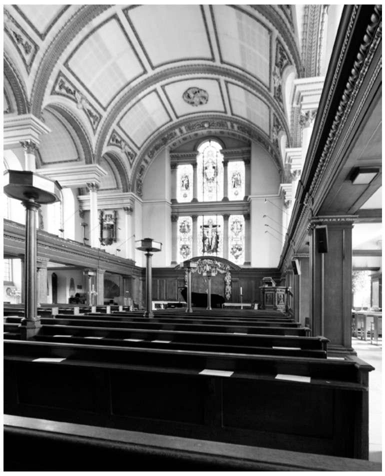


Fig. 10 Christopher Wren, St. James's, Piccadilly, Interior. Author

As Summerson reminds us, Wren would not recognize the modern distinction between *scientific* and *artistic* modes of thought and action (Summerson 1990). Nonetheless his designs for the Sheldonian Theatre and the city churches mark a fundamental shift of method when compared with that of Robert Smythson less than a century before. This is not a question of stylistic change—although Wren's buildings are clearly 'classical,' whilst Smythson's are not. What is identifiable in these latter buildings is their direct response to the specific requirements of their use: university ceremonies or a new conception of religious space. Before the availability of effective forms of artificial light, daylight was the only means of achieving high levels of illumination in buildings. Wren's designs achieve this by placing and sizing windows to maximize the view of unobstructed sky in the spaces in arrangements that respect the formal rules of classical composition, what Summerson described as "the natural equivalent of scientific thought." (Summerson 1990: 102) Clear glass and light colored interior finishes reinforce the result. The prescription for hearing in the city churches could equally apply to the satisfactory acoustics of the Sheldonian.

We have no documentary evidence of Wren directly applying *scientific* procedures in designing the environments in these buildings, but his 'weather–clocks' and other experiments with meteorological instruments tell us that he had a direct, quantitative interest in meteorology, which would help inform judgments about buildings. Similarly, an astronomer's understanding of the sun's movement in relation to the earth would bring precision to an architect's ability to achieve both practical and artistic illumination in spaces. This is amply shown in the diversity of lights found in the city churches (Hawkes 2012). In little over half a century after Robert Smythson's last buildings, architecture in Britain was changed almost beyond recognition, and we may propose that in Wren's work, the art of architecture had found common ground with the emerging organized science represented by the Royal Society of which he was a founding member and an active participant for many years.

Architecture and Science: Eighteenth Century

15 John Summerson, Architecture in Britain 1530–1830, op cit. 317)

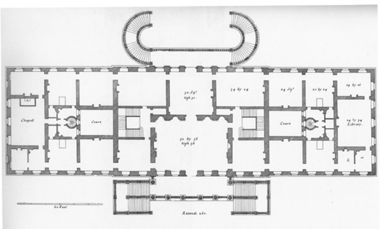


Fig. 11 Colen Campbell, Wanstead House, Plan. Colen Campbell, *Vitruvius Britannicus,* Vol. 1 (1715)

Summerson tells us that English architecture in the first half of the eighteenth century was the product of the "Rule of Taste."[15] The common label for this architecture is 'Palladian' and Summerson locates its origins in the publication of two books, Colen Campbell's Vitruvius Britannicus (Campbell 1715–1725) and the first English translation, by Giacomo Leoni, of Andrea Palladio's I quattro libri dell'architettura (Leoni 1715). Campbell's book is a collection of engravings of English country houses in the classical manner by architects including Wren, Thomas Archer, Inigo Jones and Campbell himself. The text is almost entirely descriptive, giving dimensions of the buildings, discussing the materials used and aspects of classical style. In comparison, Palladio's celebrated text is a comprehensive manual on all aspects of architecture. It is, of course, an architecture that is precisely located in the conditions, cultural and geographical, of Italy. On the environmental matters that are our concern here, the prescriptions for the orientation of rooms, the dimensioning of windows or the size and location of fireplaces and chimneys, are all calibrated to the Italian climate and, specifically, to that of the Veneto.

16 Robert Morris (1728): *An Essay in Defence of Ancient Architecture*, London. Robert Morris (1734-36): *Lectures on Architecture*, 2 Vols., London. Robert Morris (1750): *Rural Architecture*, London. Robert Morris (1751): *Architectural Remembrancer*: London.

The English Palladians, from the outset, were alert to the different condition of the English climate to which they quite precisely adapted their designs. In the first volume of Vitruvius Britannicus, Campbell (1676–1729) illustrated his design for Wanstead House (1715–1720) (fig. 11). An indication of this climate adaptation is illustrated by the larger sizes of windows in relation to rooms compared to the Italian precedent. This provides more light under the duller skies whilst avoiding the overheating of the Italian sun. Palladio also recommended that fireplaces should be placed on outside walls, but at Wanstead, they are on internal walls in the traditional English manner that allows heat to be retained in the core of the building.

An important event in the translation of Palladian principles to the English context came with the writings of Robert Morris (1703–1754). Describing himself as a 'Surveyor', Morris published a number of works on architecture in the first half of the eighteenth century.[16] Of particular relevance here are the "Lectures on Architecture" (Morris 1734–1736). Broadly conforming to the model of Palladio's treatise, the lectures comprised a broad historical review, a discourse on proportion and illustrations of unbuilt designs by the author. But, it is their relationship to the new scientific culture in England that is most relevant here. Tanis Hinchcliffe has argued that the Lectures were conceived in "a language close to the Newtonian tradition of scientific lectures and publishing" (Hinchcliffe 2004: 129). A key element of that tradition was the application of rational principles to actions in the natural world. Hinchcliffe writes:

> For Morris, architecture existed in the physical world, where there is natural and artificial architecture, but the physical world should be

experienced through experiment, not simply through custom. Just as he would have encountered experiments in the public display of science, so Morris recommends that building technology be handled experimentally on a day–to–day basis by those engaged in the process. (Hinchcliffe 2004: 130)

In translating 'rational principles' into practical guidance for architecture, Morris adopted the Newtonian practice of quantifying and tabulating information. In Lecture II the influence of Newton is apparent when introducing the subject of lighting rooms:

> OPTICKS will be requisite to be understood, as far as they relate to Proportions of Light in large or small Rooms, or as the Situation is as to the four Cardinal Points [...]. (Morris 1734-36: 28)

In Lecture VII a procedure is given for determining the dimensions of windows,

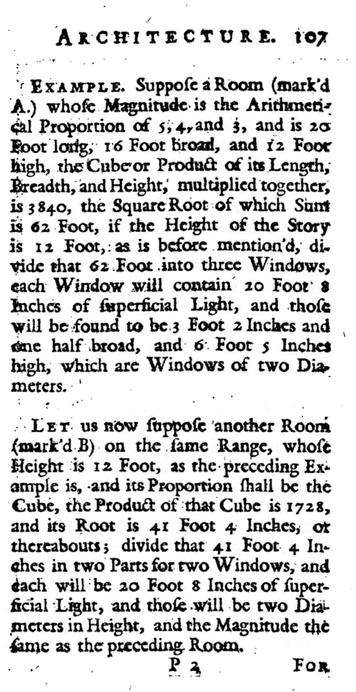
> by which any room may be illuminated more or less according to the Uses of them [...]
> Let the Magnitude of the Room be given, and one of those Proportions I have propos'd to be made use of, or any other; multiply the Length and Breadth of the Room together, and that Product multiply by the Height, and the Square Root of that Sum will be the Area or superficial Content in Feet, etc. of Light requir'd. (Morris 1734 y36: 107)

This clearly derives from Palladio's method in Chapter XXV of the First Book, but is more explicit in its formulation by giving 'worked examples' for various types and sizes of rooms (fig. 12). It also differs in that the resultant windows are consistently larger in relation to the rooms they serve than the Italian examples, making them appropriate to the duller light of England.

Lecture VI is concerned with the 'Situation' of houses and it is here that the relevance of the four Cardinal Points becomes apparent.

> The South Aspect is most preferable for the principal Front, if it can be conveniently had, in which should be the Rooms of State and Grandeur. The East is the most proper for a Library, because in the Morning Sun gives an enlivening Warmth to nature [...]. (Morris 1734-36: 89)

The lecture concludes with a discourse on the calculation of sizes of Chimnies in relation to the dimensions of rooms. The formula is summarized in "A Table of Harmonick and Arithmetical Proportions for Magnitudes of Rooms and Chimnies by Universal Rules" (fig. 13).



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EXAMPLE. Suppoſe a Room (mark'd A.) whoſe Magnitude is the Arithmetical Proportion of 5, 4, and 3, and is 20 Foot long, 16 Foot broad, and 12 Foot high, the Cube or Product of its Length, Breadth, and Height, multiplied together, is 3840, the Square Root of which Sum is 62 Foot, if the Height of the Story is 12 Foot, as is before mention'd, divide that 62 Foot into three Windows, each Window will contain 20 Foot 8 Inches of ſuperficial Light, and thoſe will be found to be 3 Foot 2 Inches and one half broad, and 6 Foot 5 Inches high, which are Windows of two Diameters.

LET us now ſuppoſe another Room (mark'd B) on the ſame Range, whoſe Height is 12 Foot, as the preceding Example is, and its Proportion ſhall be the Cube, the Product of that Cube is 1728, and its Root is 41 Foot 4 Inches, or thereabouts; divide that 41 Foot 4 Inches in two Parts for two Windows, and each will be 20 Foot 8 Inches of ſuperficial Light, and thoſe will be two Diameters in Height, and the Magnitude the ſame as the preceding Room.

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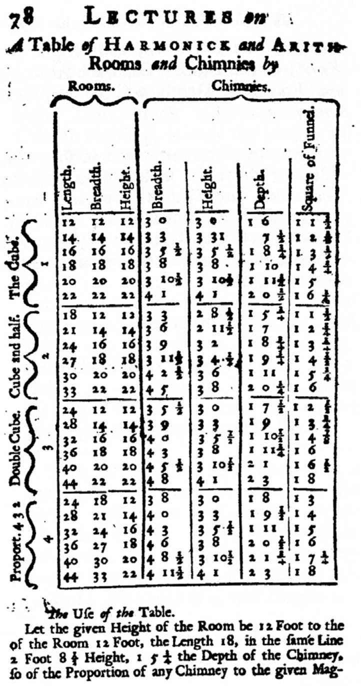
Fig. 12 Robert Morris, Window Rules. Robert Morris, *Lecture on Architecture* (1734)



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A Table of HARMONICK and ARITH- Rooms and Chimnies by

	Rooms. Length.	Rooms. Breadth.	Rooms. Height.	Chimnies. Breadth.	Chimnies. Height.	Chimnies. Depth.	Chimnies. Square of Funnel.
The Cube. 1	12	12	12	3 0	3 0	1 6	1 1 ½
	14	14	14	3 3	3 3	7 ½	1 2 ⅛
	16	16	16	3 5 ½	3 5 ½	1 8 ¼	1 3 ½
	18	18	18	3 8	3 8	1 10	1 4 ½
	20	20	20	3 10½	3 10½	1 11½	1 5
	22	22	22	4 1	4 1	2 0 ½	1 6 ½
Cube and half. 2	18	12	12	3 3	2 8 ½	1 5 ¼	1 1 ½
	21	14	14	3 6	2 11½	1 7	1 2 ¼
	24	16	16	3 9	3 2	1 8 ¼	1 3 ¼
	27	18	18	3 11½	3 4 ½	1 9 ¼	1 4 ½
	30	20	20	4 2 ½	3 6	1 11	1 5 ¼
	33	22	22	4 5	3 8	2 0 ¼	1 6
Double Cube. 3	24	12	12	3 5 ½	3 0	1 7 ½	1 2 ⅛
	28	14	14	3 9	3 3	1 9	1 3 ¾
	32	16	16	4 0	3 5 ½	1 10½	1 4 ⅞
	36	18	18	4 3	3 8	1 11¾	1 6
	40	20	20	4 5 ½	3 10½	2 1	1 6 ½
	44	22	22	4 8	4 1	2 3	1 8
Proport. 4 3 2 4	24	18	12	3 8	3 0	1 8	1 3
	28	21	14	4 0	3 3	1 9 ½	1 4
	32	24	16	4 3	3 5 ½	1 11	1 5
	36	27	18	4 6	3 8	2 0 ½	1 6
	40	30	20	4 8 ½	3 10½	2 1 ¼	1 7 ¼
	44	33	22	4 11½	4 1	2 3	1 8

The Uſe of the Table.

Let the given Height of the Room be 12 Foot to the of the Room 12 Foot, the Length 18, in the ſame Line 2 Foot 8 ½ Height, 1 5 ¼ the Depth of the Chimney, ſo of the Proportion of any Chimney to the given Mag-

Fig. 13 Robert Morris, Chimnies Dimensions. Robert Morris, *Lecture on Architecture* (1734)

A quarter of a century after Morris delivered his lectures came William Chambers' (1723–1796) A Treatise on the Decorative Part of Civil Architecture (Chambers 1759). This also follows the model of Palladio, but is more explicit than Morris in its translation of the specific details of design to the English condition.

> In Italy, and some other hot countries, although the windows are less in general than ours, their apartments cannot be made habitable, but by keeping the window shutters almost closed, while the sun appears above the horizon. But in regions where gloom and clouds prevail eight months of the year, it will always be right to admit a sufficiency of light for those melancholy seasons [...] (Chambers 1759: 115)

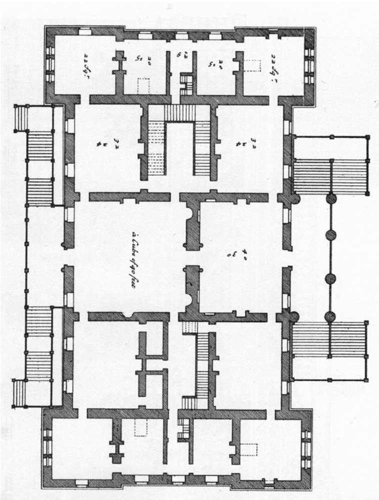

Fig. 14 Houghton Hall, Piano Nobile Plan. Colen Campbell, *Vitruvius Britannicus,* Vol. 3 (1725)

Fig. 15 Lord Burlington, Chiswick House, Exterior. Author

In the new *scientific* spirit, Chambers declares Palladio's formula for window size to be "surely too vague" (Chambers 1759: 116) and, on the authority of his own practice, proposes an alternative:

> I have generally added the depth and the height of the rooms on the principal floor together, and taken one–eighth part thereof, for the width of the window; a rule to which there are few objections; admitting somewhat more light than Palladio's, it is, I apprehend, fitter for our climate than his rule would be [...]. (Chambers 1759: 116)

Chambers also confirms that Palladio's practice of placing fireplaces on the outer wall of a building was unsuitable in England. "[T]his must be avoided for [...] the chimney shafts at the top of the building, which must necessarily be carried higher than the ridges of the roofs, have from their great length, a very disagreeable effect [...]." (Chambers 1759: 126) A simple formula is then given by which to calculate the size of a fireplace in relation to the dimensions of a room.

Theory and practice enjoy a curious relationship in the architecture of eighteenth century England. It is clear that the publication of Campbell's Vitruvius Britannicus and the English translation of Palladio had a profound, formative influence on practice, but it is an intriguing fact that the precise adjustments of the Italian precedents to the different conditions of the English climate were anticipated in the first great Palladian houses, all of which pre–date the writings of Morris and Chambers. Wanstead (1715–1720) was demolished in 1820, but Houghton Hall (1722–1725), Mereworth Castle (1723) and Chiswick House (1725–1729) all survive and display windows larger than those found in the Veneto. Similarly the provision of fireplaces and chimneys is generous in number and dimension and almost always these are located on the inner walls, as may be seen in the plan of Houghton (fig. 14). The exception to this rule is at Chiswick where the fireplaces are, as at Palladio's Rotonda, on the outer walls, although the obelisk–like chimneys rise higher above the eaves than those at Vicenza, as was later stipulated by Chambers (fig. 15).

Summerson suggests that the English architects of the eighteenth century, in adopting the Palladian 'style,' were seeking to make a clean break from the earlier tradition of classical architecture in the country, "the works of Sir Christopher Wren in particular and anything in the nature of Baroque." (Summerson 1969: 317) On the other hand, it may be argued that the 'new' architecture embraced a "scientific cast of mind" (Hinchcliffe 2004: 127-138) that, although influenced by Newtonian codification and tabulation, may be traced back to the combination of scientific thought and architectural design that was developed by Christopher Wren in the previous century.

Conclusion

This paper has sought to uncover the way in which architecture and science in England were inter–related in the two hundred years between the last decades of the sixteenth to the middle of the eighteenth centuries. Through the remarkable and original houses built by Robert Smythson we may see that the relationship between building and climate—the extreme climate of the 'Little Ice Age'—achieved a consistency and precision of design that moves beyond the conventions and practices of vernacular precedent. In this sense they are becoming *scientific*. Christopher Wren was a scientist who became an architect. This relationship has been previously discussed in broad critical terms,[17] but the present study shows that Wren's work in the field of meteorology, in tandem with the implications of his understanding of astronomy for the natural lighting of buildings, make him possibly the first *building scientist*. In the eighteenth century, the architecture of the English Palladians became allied to the "scientific cast of mind" that spread through the culture under the influence of Newton. The treatises of Morris and Chambers adopted Newtonian codification and tabulation in recalibrating the Italian architecture of Palladio to the different conditions of England, thus combining architectural style with the numerical systems of science.

The conventional reading of the relation between science and architecture rests upon the link between science and technology that emerged at the end of the eighteenth century, as new methods of construction and of environmental provision were taken into building practice. By the twentieth century, for some, architecture and technology had become almost inseparable. "A breach has been made with the past, which allows us to envisage a new aspect of architecture corresponding to the technical civilization of the age we live in." (Gropius 1935: 19) In twenty–first century theory and practice, it is almost inconceivable that a building would not involve some measure of numerical calculation in the design of its structure, fabric, or, in

17 John Summerson, "The Mind of Wren," op cit and J.A. Bennett, *The Mathematical Science of Christopher Wren*, op cit.

relationship to the present discussion, its environmental services. To paraphrase Siegfried Giedion: mechanization has taken command. This paper argues that science in architecture has a validity and relevance that is independent of the conventional instrumental relationship between science and technology. The pre–industrial buildings of Smythson, Wren, and the English Palladians were conceived within an evolving conception of science that carries implications for our present understanding of this complex relationship. They show us that scientific understanding of the natural world may be seamlessly incorporated into the processes by which architecture is conceived, that a building may be scientific without recourse to literal translation of its science into technological expression.

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Recommended Citation

Hawkes, Dean: The Origins of Building Science in the Architecture of Renaissance England. In: Wolkenkuckucksheim, Internationale Zeitschrift zur Theorie der Architektur. Vol. 19, Issue 33, 2014, [pages], cloud-cuckoo.net/fileadmin/issues_en/issue_33/article_hawkes.pdf [inquiry date].