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Abstract. This essay follows recent work in environmental history to explore the history of recycling in physical sciences in Britain and North America since the seventeenth century. The term 'recycling' is here used broadly to refer to a variety of practices that extended the life of material resources for doing science in the early modern period. These included practices associated with maintenance, repair, exchange and the adaptation or reuse of material culture. The essay argues that such practices were common in early modern science, and informed experimental spaces and techniques and the ideas that they generated. The essay considers some of the varied motivations that led to such practices, and concludes by examining the endurance of recycling in science since the end of the eighteenth century, particularly in recent efforts to create sustainable scientific research practices.

In recent years social and environmental historians have begun to explore the history of recycling. Although the term 'recycling' originated in the 1920s, and was only applied to the environmental reprocessing of waste materials in the 1970s, the associated practices are much older. Historical studies have thus examined not only the transformation of waste matter into raw materials, but also the reuse and adaptation of old materials to new ends, in addition to activities such as maintenance, repair and restoration. In a pioneering work, Susan Strasser examined changing approaches to the reuse and disposal of waste in the nineteenth- and twentieth-century North American domestic context.[1] For the same period, Martin Melosi and Sabine Barles have explored industries managing refuse and garbage in the United States and France respectively.[2] Tim Cooper and Nicolas Goddard have considered waste management and the use of discarded materials in agriculture and sanitation in Victorian Britain, and Zsuzsa Gille has examined recycling in Socialist Hungary in the twentieth century.[3]

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1 Susan Strasser, *Waste and Want: A Social History of Trash*, New York: Metropolitan Books, 1999.

2 Martin V. Melosi, *Garbage in the Cities: Refuse, Reform, and the Environment*, Pittsburgh: University of Pittsburgh Press, 2004; Sabine Barles, *L'invention des déchets urbains: France 1790–1970*, Seyssel: Champ Vallon, 2005.

3 Tim Cooper, 'Rags, bones and recycling bins', *History Today* (2006) 56, pp. 17–18; Nicholas Goddard, '19th-century recycling: the Victorians and the agricultural use of sewage', *History Today* (1981) 31, pp. 32–36; Zsuzsa Gille, *From the Cult of Waste to the Trash Heap of History: The Politics of Waste in Socialist and Postsocialist Hungary*, Bloomington, IN: Indiana University Press, 2007; see also Erland Mårald, 'Everything circulates: agricultural chemistry and recycling theories in the second half of the nineteenth century', *Environment and History* (2002) 8, pp. 65–84.

Despite the obvious intimacy between current environmental recycling and communities of technical experts, there has as yet been no study of the history of recycling in the sciences. This essay offers an initial examination of the subject by considering techniques of scientific recycling in the seventeenth and eighteenth centuries. This period has received scant attention from historians of recycling.[4] Historians of science long associated the era primarily with *innovation*, assuming that the age of the 'Scientific Revolution' was principally marked by a rejection of the old (the ancients, scholasticism) in favour of novelty – new instruments, new methods and new knowledge. More recently, historians of science have shifted their attention from studying innovation and the production of knowledge to its consumption, dissemination and circulation.[5] Historians and sociologists of technology have similarly been keen to explore the ways technology is used rather than focus on the process of invention.[6] Such approaches point to the need for a better appreciation of everyday scientific and technical practices, and the significance they give to existing ideas, techniques and objects. An examination of the history of recycling in the sciences contributes to this approach by revealing an aspect of the circulation of scientific materials and practices that has hitherto been ignored.

Consequently, this essay proposes that from the perspective of practice and material culture, the 'new' science in fact remained very much connected with the old, as early modern natural philosophers engaged in a variety of efforts to adapt, reuse and carefully deploy old materials, existing instruments and scarce substances in their experimental investigations. The essay begins by exploring the early modern domestic culture of 'making do', the careful stewardship of materials and artefacts in the face of expense and scarcity, and then suggests that natural philosophers also 'made do' in the seventeenth and eighteenth centuries, extending practices from the household, artisanal practice and waste trades into the new science. I begin with a discussion of the ways philosophers adapted domestic space to science, following which a variety of techniques are considered which entailed the use of old materials, adaptation, reuse and repair in early modern experimental settings. The motivations for such actions, some general and some more specific to the sciences, will then be discussed, before the conclusion briefly compares early modern practices of making do with approaches to waste and recycling in later periods.

It should be made clear that this is not meant to be a survey of all sciences: most of the examples will come from chemistry and physical sciences, which are the author's area of expertise, but this is not supposed to be representative. It will remain a question whether

4 But see Donald Woodward, 'Swords into ploughshares: recycling in pre-industrial England', *Economic History Review* (1985) 38, pp. 175–191; Beverly Lemire, 'Consumerism in pre-industrial and early industrial England: the trade in second-hand clothes', *Journal of British Studies* (1988) 27, pp. 1–24; Laurence Fontaine (ed.), *Alternative Exchanges: Second-Hand Circulations from the Sixteenth Century to Today*, Oxford: Berghahn Books, 2008.

5 On circulation see James Secord, 'Knowledge in transit', *Isis* (2004) 95, pp. 654–672; David Livingstone, *Putting Science in Its Place: Geographies of Scientific Knowledge*, Chicago: University of Chicago Press, 2003, pp. 135–178.

6 David Edgerton, *The Shock of the Old: Technology and Global History since 1900*, Oxford: Oxford University Press, 2007; Nelly Oudshoorn and Trevor Pinch (eds.), *How Users Matter: The Co-construction of Users and Technology*, Cambridge, MA: MIT Press, 2003.

recycling practices in, say, natural history or astronomy were different to those in other sciences. In addition, the geographical scope is limited largely to Britain and North America, occasionally extending to other areas when relevant. While I shall touch on some of the geographical variation in recycling practices, a representative or comparative study of different regions will remain a goal for the future. Lastly, I cannot yet offer a neat definition of the limits of what counted as practices of adaptation, reuse, repair and so on in the early modern world, and I am not sure that such a definition can be achieved. Rather, I merely wish to draw attention to a set of practices which have otherwise been overlooked by historians of science, and which, I would argue, constituted a significant aspect of scientific activity in the early modern period. That significance lies partly in the ways that consideration of scarce materials, limited resources and the need to 'make do' shaped natural philosophers' decisions about the uses of scientific sites, instruments and experimental agendas, as examples in the following should make clear.

'Making do' and making space for science

The American social historian Susan Strasser has pointed to the value placed on 'the stewardship of objects' in the early modern period.[7] For Strasser, the stewardship of objects refers primarily to a widespread care over materials which operated in households. Strasser describes the routine efforts of men and women to 'make do' in this context, improvising with available materials, keeping domestic or workshop utensils in good repair, and reusing objects for other purposes. As she puts it, focusing on the case of colonial American households, people

> mended, reused, saved, and made do. They darned socks and fed food scraps to chickens and pigs. They dyed faded dresses and repaired rickety furniture. They handed things down to younger and poorer relatives or to servants; they turned old clothes and sewing scraps into rugs, quilts, and other home furnishings.[8]

Materials were repaired, reused, used by friends or relatives, or converted to new uses. For most people, scarcity, and to a lesser extent poverty, dictated that such activities were a matter of course. As Strasser puts it, 'Everyone was a bricoleur'.[9] Reuse was not a choice, an alternative to throwing things away, but the norm, a situation reflected in the fact that there was no special vocabulary for these practices in the early modern world. Making do was just what was done.

'The stewardship of objects', 'bricolage' and 'making do' are thus Strasser's categories, not those of contemporaries, but they do capture a form of life which was widespread.

7 Strasser, op. cit. (1). The use of the term 'stewardship' has been criticized in environmental studies, but here it is only meant to designate a form of careful management intended to preserve and make good use of materials.

8 Strasser, op. cit. (1), p. 22; see also Heather Rogers, *Gone Tomorrow: The Hidden Life of Garbage*, New York: New Press, 2005, pp. 29–32.

9 Strasser, op. cit. (1), pp. 22–23.

Stewardship extended from the household to more widely distributed networks of artisans who made their living trading in old and discarded materials. From the fourteenth century in many European cities, scavengers of a new class were employed by municipal authorities to roam the streets with carts collecting waste. Coal ashes, bones, rags, cinders, night-soil, metals and shells were all gathered and refashioned into useful products.[10] In early eighteenth-century England, cast-off clothes were sold in London by the 'old-clothes-men of Rag Fair and Rosemary-Lane'.[11] Port towns such as Bristol, Hull and Yarmouth traded in old iron, bullets and cannon, and old cordage and sails were used to make brown paper in mills near Exeter and Southampton. Old wax, broken glass and old shoes were also collected for reuse.[12]

The stewardship of objects also extended to the practitioners of science. If we associate the early modern period with a '*new* science' it was also one in which the sciences remained very much engaged, on a practical level, with the old, as philosophers routinely repaired, reused and made do with material culture. Natural philosophers adapted methods from domestic and artisanal practice, which they knew as householders or by seeking out information from skilled workers, merchants and craftsmen. This is evident first in the places where natural philosophy occurred in the early modern period. Steven Shapin long ago noted that, in the seventeenth century, 'The overwhelming majority of experimental trials, displays, and discussions that we know about occurred within private residences.'[13] Most experimental inquiry took place in adapted domestic spaces, sometimes known as 'laboratories' if they entailed chemical or pyrotechnic work.[14] Shapin and Deborah Harkness have highlighted the social tensions that such novel arrangements produced in early modern households, and Harkness stresses that this period was distinctive for adapting space to science, following the medieval pursuit of science in monasteries and the future use of dedicated laboratories for experimental inquiry.[15] It is notable that adaptation of existing space, rather than the construction of new sites, was so common, and this might be seen as part of a culture of making do. After all, the wealthy Robert Boyle could have afforded to build new spaces for science, but it was presumably simpler to adapt existing space. Indeed, Boyle and others exhibited a skill for turning the features of existing space to philosophical advantage, and this suggests the value of making do for early modern experiment.

10 On early modern waste disposal, see Emily Cockayne, *Hubbub: Filth, Noise and Stench in England, 1600–1770*, New Haven: Yale University Press, 2007, pp. 183–191.

11 Quoted in Woodward, op. cit. (4), p. 178; 'Scavengers', *A New and Complete Dictionary of Arts and Sciences … The Second Edition*, vol. 4, London, 1764, p. 2879.

12 The examples are taken from Woodward, op. cit. (4), pp. 186, 188–189.

13 Steven Shapin, 'The house of experiment in 17th-century England', *Isis* (1988) 79, pp. 373–404, 378.

14 Pamela H. Smith, 'Laboratories', in Lorraine Daston and Katharine Park (eds.), *The Cambridge History of Science*, vol. 3: *Early Modern Europe*, Cambridge: Cambridge University Press, pp. 290–305; Maurice Crosland, 'Early laboratories *c.*1600–1800 and the location of experimental science', *Annals of Science* (2005) 62, pp. 233–253.

15 Harkness writes, 'for a relatively brief time the household bridged the gap between monastery and laboratory as a site for the practice of natural philosophy'. Deborah E. Harkness, 'Managing an experimental household: the Dees of Mortlake and the practice of natural philosophy', *Isis* (1997) 88, pp. 247–262, 249.

The kitchen, for example, provided a ready source of fire and materials for chemical experiments. Investigating freezing, Boyle borrowed from kitchen practice when he considered the use of snow and salt to cool drinks and fruit. Trying other mixtures to see if they produced the same effect, he buried drinking-glasses in a mixture of snow, vinegar and 'Kitchin sugar'.[16] Investigating porosity, Boyle kept bones close to a kitchen fire to keep them dry.[17] Boyle also exploited the conditions of his cellar to experimental ends. He compared the temperature of a cellar on a frosty night with the outside air and the temperature of his bedchamber, noting that cellars remained above freezing, so that beer did not freeze in them.[18] He described how to preserve fruit and flowers for a year by burying them inside glasses in a cellar.[19] And he investigated the insensible agitation of fluid bodies by placing fused salt of tartar in his cellar, where the moist air dissolved it into a clear liquor.[20]

The bedchamber also served as an experimental site. Boyle's bedroom window provided a place for experiments. Investigating whether metal particles would preserve a blue tincture from putrefaction, Boyle noted that although 'the Vial was left unstopt in a window in my Bed-Chamber for many weeks, yet I (whose Organs of smelling are very tender, and who did often put the Vial to my Nose) did not perceive the Liquor to grow at all stinking'.[21] On another occasion, Boyle compared the rise and fall of mercury in an inverted glass tube with the actions of a weather-glass by observing it in his bedchamber:

> having put both the Tube and the Vessel it lean'd on into a convenient Wooden frame to keep them from mischances: we plac'd that Frame in a Window within my Bed-chamber, that I might both keep the Mercury from being stirr'd, and have opportunity to watch from time to time the Phaenomena it was to exhibit.[22]

The frame and the bedroom window allowed Boyle to keep the apparatus safe and helped him to observe the tube over a period of several weeks.

Particular rooms thus provided particular conditions and material opportunities for experiment. Boyle was not alone in adapting spaces in this way. Newton famously controlled the light entering from the windows of his rooms in Cambridge to aid his optical investigations. Earlier, in the 1630s, Kenelm Digby used the window of his rooms in Gresham College, several of which he adapted into a laboratory, to congeal a lye made from nettles: 'I calcined [nettles] in the fair and large Laboratory, that I had erected under the Lodgings of the Divinity Reader: And I exposed the lye to congeale in the Window of

16 Robert Boyle, *New Experiments and Observations Touching Cold, or, An Experimental History of Cold*, London, 1665, pp. 109–132.

17 Robert Boyle, *Experiments and Considerations about the Porosity of Bodies in Two Essays*, London, 1684, p. 63.

18 Robert Boyle, 'Memoirs for an experimental history of cold', in *Philosophical Works of the Honorable Robert Boyle*, ed. Peter Shaw, 3 vols., London, 1738, vol. 1, pp. 573–730, 652.

19 Robert Boyle, 'The usefulness of experimental philosophy; by way of extortion to study it', in *Philosophical Works of the Honorable Robert Boyle*, op. cit. (18), vol. 1, pp. 3–181, 109.

20 Robert Boyle, *Certain Physiological Essays and Other Tracts Written at Distant Times, and on Several Occasions*, London, 1669, p. 189.

21 Robert Boyle, *Memoirs for the Natural History of Humane Blood, Especially the Spirit of that Liquor*, London, 1683, p. 76.

22 Robert Boyle, *New Experiments Physico-mechanical, Touching the Air*, London, 1682, pp. 63–64.

my Library, among my Lodgings at the end of your Great Gallery.'[23] White nettles appeared in the frozen lye, showing that flowers and plants could be reconstituted from their own ashes, part of a larger investigation into the resurrection of plants and animals from their calcined ashes.

Francis Bacon noted the value of cellars for congealing substances, and how phosphorescent materials retained their lustre longer in cellars than elsewhere.[24] In *New Atlantis*, Bacon described deep caves of the 'Lower Region': 'we use them for all coagulations, indurations, refrigerations, and conservations of bodies'.[25] Bacon reckoned that domestic spaces were essential to natural philosophy, even if they were considered lowly:

> There is a strange Reluctance, and a kind of Loathing in the Mind, with regard to *mechanical Experience*, and the homely Observations of the *Kitchen*, the *Dairy*, the *Cellar*, servile Arts, and the like: and yet the most necessary, and serviceable part of all *Natural Philosophy*, must be derived from such Observation.[26]

Alchemy and magic no doubt provided some of the inspiration for such comments. Kitchens were long used by alchemists, as depicted in Pieter Bruegel's well-known engraving *The Alchemist in the Peasant's Kitchen* (1558). Bruegel's image recalls the social tensions of adapted space noted by Shapin and Harkness, with the children exiled to play at the edge of the room and outside in the yard as the alchemist vainly seeks after gold in the kitchen.[27] Meanwhile, alchemists learned from culinary technique. Aristotle took terms such as 'roasting' and 'boiling' from cookery to describe natural processes, and alchemists such as Geber took from this the idea that alchemy could use artificial means to imitate nature's generative processes, employing only the ingredients used by Nature.[28] Early modern court apothecaries were also typically adapted kitchens, so that, as Bruce Moran has written, 'the line between kitchen and apothecary was not always clearly defined'.[29] Early modern books of secrets and natural magic typically included cooking recipes and in the early seventeenth century they invited women to pursue distillation and the preparation of medicines in their kitchens.[30] Making do with

23 Sir Kenelm Digby, *A Discourse Concerning the Vegetation of Plants Spoken by Sir Kenelme Digby at Gresham College on the 23 of January, 1660*, London, 1661, pp. 76–77. On Digby's laboratory see Mordechai Feingold, *The Mathematicians' Apprenticeship: Science, Universities and Society in England, 1560–1640*, Cambridge: Cambridge University Press, 1984, pp. 181–182.

24 Francis Bacon, *The Philosophical Works of Francis Bacon, Baron of Verulam*, ed. Peter Shaw, 3 vols., London, 1733, vol. 3, p. 121.

25 Bacon, op. cit. (24), vol. 1, p. 291.

26 Bacon, op. cit. (24), vol. 3, p. 12.

27 On the Bruegel image see Lawrence M. Principe and Lloyd DeWitt, *Transmutations: Alchemy in Art: Selected Works from the Eddleman and Fisher Collections at the Chemical Heritage Foundation*, Philadelphia: Chemical Heritage Foundation, 2002, pp. 11–12.

28 William R. Newman, *Promethean Ambitions: Alchemy and the Quest to Perfect Nature*, Chicago: University of Chicago Press, 2004, pp. 73–74.

29 Bruce Moran, *Distilling Knowledge: Alchemy, Chemistry, and the Scientific Revolution*, Cambridge, MA: Harvard University Press, 2005, p. 53.

30 Moran, op. cit. (29), pp. 62–64; Allison Kavey, *Books of Secrets: Natural Philosophy in England, 1550–1600*, Champaign: University of Illinois Press, 2007, pp. 95–125.

existing space thus generated new forms of space and new social or gender opportunities and tensions in the household.

Recycling techniques in experimental settings

That such adaptations might be seen as belonging to a culture of 'making do' is supported by reviewing some of the practices that natural philosophers undertook within their adapted spaces. Natural philosophers, like householders and artisans, worked to preserve material culture, to reuse old materials and tools, and to repair broken items, so that a significant component of early experimental practice emerged from acts of making do. Techniques came from a variety of sources. Some followed everyday and domestic practice, some were borrowed from artisans, others were exclusive to natural philosophers.

Obtaining instruments and materials for early modern philosophical inquiry entailed producing them oneself, purchasing them, receiving them as gifts or recycling or adapting them from existing artefacts. In practice, these activities should not be sharply distinguished – there was rarely a clear line separating the 'new' and the 'used'. This is because production might incorporate old materials, purchases of new goods might be made with a mind to the durability and ease of repair of the item purchased, and adaptation might incorporate new elements into an existing artefact.

Obviously, many of the instruments used by philosophers were new, purchased from instrument-makers or made by hand, but these might incorporate old or cheap materials or adapt existing components. As such, philosophers followed the normal domestic practice of 'bricolage' in using old materials to make new things, such as clothes. In the seventeenth century, for example, Samuel Pepys, president of the Royal Society, wore a 'grey cloth suit and faced white coat, made of one of my wife's petticoats'.[31] Similarly, philosophical instruments were made with used materials. It has been estimated that some 10 per cent of all iron used in seventeenth-century England was recycled, and the trade in 'old brass' was international. Galileo purchased old brass for his instrument-maker Mazzoleni from Germany, for a third of the price of new, and made his first telescopes using organ pipes and lenses ground on a cannon ball.[32] Alternatively, cheap materials could replace more expensive ones, as when astronomical instruments such as astrolabes were made from paper.[33]

Natural philosophers also adapted domestic goods and waste to philosophical uses. It is well known that a variety of pots, pans, jugs and bottles were used in early modern experiments.[34] James Watt famously deployed a kettle to investigate steam, and

31 Quoted in Woodward, op. cit. (4), pp. 177–178.

32 Woodward, op. cit. (4), pp. 185–186; Giorgio Strano, 'Galileo's telescope: history, scientific analysis, and replicated observations', *Experimental Astronomy* (2009) 25, pp. 17–31, 22.

33 Owen Gingerich, 'Astronomical paper instruments with moving parts', in Robert Anderson, James A. Bennett and W.F. Ryan (eds.), *Making Instruments Count: Essays on Historical Scientific Instruments presented to Gerard L'Estrange Turner*, Aldershot: Variorum, 1993, pp. 63–74.

34 Elaine Leong has highlighted the use of cooking and household implements in the making of medicaments in early modern households. See her 'Making medicines in the early modern household', *Bulletin of the History of Medicine* (2008) 82, pp. 145–168, 162; see also J.M. Enoch, 'Nicholas de Cusa

Joseph Priestley often adapted household utensils to chemical ends, making an earthen trough to collect gases with a container 'commonly used for washing linen' which he passed on to a friend after he had finished with it.[35] Priestley used gun barrels and broken tobacco pipes to extract air from solids, generated fixed air by adding acid to 'sawings of marble', and carried jars of air around immersed in water on 'common tea-dishes.'[36] This practice extended to less obvious artefacts, such as playing cards. Because early modern playing cards were only printed on one side, the blank sides of defunct cards were used for a variety of purposes, as notepaper, as calling cards or even as a form of currency. Dr John Morgan of the College of Philadelphia, later the University of Pennsylvania, thus advertised 'A course of lectures on the materia medica' on a playing card in 1765.[37] Domestic space, Morgan's house, provided the venue for the lectures, while the card was made authoritative by applying Morgan's wax seal below his announcement. Botanists may have taken playing cards into the field to make notes on. In 1783 the French naturalist Jean-Pierre Bergeret proposed that the principles of his new system of botanical nomenclature 'can be written on fewer than twelve playing cards'.[38] Certainly Jean-Jacques Rousseau wrote his *Reveries of a Solitary Walker*, a series of philosophical contemplations, on playing cards, during countryside walks punctuated with botanizing.[39] Used cards also enabled new ways of organizing knowledge. Edward Gibbon employed old playing cards to create one of the earliest card indexes, in this case of the books in his library.[40]

Chemical substances could also be produced using old materials. James Arden's lectures on natural philosophy included the advice that after making ink, 'bits of old Iron and broken Galls kept in the Vessel with the Ink, will improve the Colour'.[41] Physicians made the emetic preparation of antimony called regulus antimonii martialis using 'common Nails or any old iron, in small Pieces, put into a large Crucible'.[42] This was fused with antimony, nitre and tartar in a furnace to produce a scoria, which was mixed

(1401–1464): a description of fine grained and polished wooden spoons employed as mirrors; concave, convex, flat and cylindrical (1450 AD)', *Hindsight* (2003) 34, pp. 1–3.

35 Maurice Crosland, 'Priestley Memorial Lecture: a practical perspective on Joseph Priestley as a pneumatic chemist', *BJHS* (1983) 16, pp. 223–238, 233; on Watt see Richard L. Hills, *James Watt*, vol. 1: *His Time in Scotland, 1736–1774*, Ashbourne: Landmark Publishing, 2002.

36 Joseph Priestley, *Experiments and Observations on Different Kinds of Air*, 3 vols., Birmingham, 1790; Kraus reprint, 1970, vol. 1, pp. 16, 20, 51. Tobacco pipes were also used as stirrers. See Robert Dossie, *The Elaboratory Laid Open: Or the Secrets of Modern Chemistry and Pharmacy Revealed*, London, 1758, p. 273.

37 General Collection of the University of Pennsylvania, 1740–1820. UPA 3. Matriculation and Lecture Ticket Collection 1620. Morgan, John. Materia. Medica and Practice of Physick: incomplete, 1765. Thanks for this reference to Karen Reeds.

38 Jean-Pierre Bergeret, *Phytonomatotechnie universelle*, Paris, 1783, p. 158. Thanks for this reference to Sara T. Scharf.

39 See Eli Friedlander, *J.J. Rousseau: An Afterlife of Words*, Cambridge, MA: Harvard University Press, 2004, pp. 74, 163.

40 British Library Add Mss 34716; Geoffrey Keynes, ed., *The Library of Edward Gibbon*, 2nd edn, Godalming: St Paul's Bibliographies, 1980.

41 James Arden, *Analysis of Mr. Arden's Course of Lectures on Natural and Experimental Philosophy*, London, 1782, p. 10.

42 Richard Bradley, *A Course of Lectures, upon the Materia Medica, Antient and Modern*, London, 1730, p. 33.

with more nitre to produce the regulus. Recipes sometimes followed folk practice, which philosophers might test and criticize. The surgeon Charles Peter thus denied that in using steel as a treatment for melancholy and other illnesses he was following the use of 'old Iron, or infusions of old Nails, for these are the common Medicines of old Women, and of some Men too, who are not of the Physick Line'.[43]

Alternatively, using old materials linked scientific and medical practitioners to larger concerns dealing in scrap and waste. In the 1730s, the physician Thomas Knight reported,

> In London it is well known, that most of the Pieces of old Iron which are gather'd by many poor People, and the impaired Pieces of Ordnance or great Guns, are sold to the Copperas Houses at Rotherhith or Debtford, which they boil up with a Dissolution of the Marcasite Pyrites, or Fire-Stone: and let the Liquor [vitriol] run out into convenient Vessels, in which it shoots into those Forms or Crystals; we meet with it amongst the Druggists.[44]

Similarly the chemist Richard Watson reported in the 1780s that green vitriol was made in Deptford by laying heaps of pyrites in the open air, which over time released 'acid of sulphur', combining with iron to produce green vitriol. This was washed into receptacles with rain water and then boiled with old iron to saturate the acid and purify it, creating 'English vitriol'. Two hundredweight of old iron produced one ton of vitriol.[45] Watson also communicated how German artisans obtained copper from 'copper water' by dissolving old iron in it to precipitate the copper.[46]

Obtaining 'new' instruments and materials thus linked natural philosophers, chemists and physicians to domestic practices, and also to international networks of artisans and merchants dealing in old materials. It was also common for philosophers to obtain materials and apparatus 'second-hand', a term originating in the fifteenth century and used to designate used goods by the seventeenth. Natural philosophers thus shared in the common practice of passing on clothes, books and material possessions between friends and relations, or from one generation to the next. Like domestic goods, scientific goods were scarce, and so exchange was just as important as production, purchase or collection, if not more so. Specimens, books and instruments were routinely exchanged in person-to-person interactions or as accompaniments to correspondence, often operating in the form of a gift economy.[47]

43 Charles Peter, *New Observations on the Venereal Disease, with the True Way of Curing the Same. The Third Edition*, London, 1709, pp. 22–23, 22.

44 Thomas Knight, *A Vindication of a Late Essay on the Transmutation of Blood, Containing The True Manner of Digestion of our Aliments, and the Aetiology*, London, 1731, p. 220.

45 Richard Watson, *Chemical Essays*, 2 vols., London, 1782, vol. 1, pp. 225–226.

46 Watson, op. cit. (45), vol. 1, p. 237.

47 Numerous instances are to be found in e.g. A. Rupert Hall and Marie Boas Hall (eds.), *The Correspondence of Henry Oldenburg*, 10 vols., Madison: University of Wisconsin Press, 1965–1975; see also Pamela H. Smith and Paula Findlen (eds.), *Merchants and Marvels: Commerce, Science, and Art in Early Modern Europe*, London: Routledge, 2001; Mario Biagioli, 'Galileo's system of patronage', *History of Science* (1990) 28, pp. 1–50, 18–25; Paula Findlen, 'The economy of scientific exchange in early modern Italy', in Bruce T. Moran (ed.), *Patronage and Institutions: Science, Technology, and Medicine at the European Court, 1500–1750*, Rochester: Boydell Press, 1991, pp. 5–24.

Philosophers often passed on scientific materials from one generation to the next, reproducing techniques and material culture through inheritance. Samuel Pepys inherited his terrella magnet from William Barlow, and Robert Boyle left his 'best microscope and … best loadstone' to Robert Hooke.[48] The lifetime of apparatus might stretch over several generations and instruments travelled long distances. After the death of the lecturer in natural philosophy John Horsley in Morpeth, Northumberland, in 1732, his lecturing instruments were purchased by Caleb Rotheram, who ran a dissenting academy in Kendal in Cumbria, after whose death they were purchased by John Holt, lecturer in natural philosophy at the Warrington Academy in Lancashire, where they were also used by Joseph Priestley. Then they were presented to Hackney New College in London in 1786, and then to the library of Dr Williams in London's Cripplegate, where they still remained in 1821.[49]

Bequests also constituted a source of instruments for institutions. In the early 1720s, Antoni van Leeuwenhoek bequeathed a collection of his microscopes contained in a small cabinet to the Royal Society, which were sent over from the Netherlands by his daughter Maria. These were not intended as 'museum pieces', since the president, Martin Folkes, made sure the microscopes could still be used, printing details of the collection in the *Philosophical Transactions* to 'be of Use, by putting any curious Observer in Mind of a Number of Minute Subjects, that may in a particular Manner deserve his Attention'.[50]

Used books, of course, were regularly sold or exchanged among the learned, assisted by a variety of second-hand booksellers, and were also sold at numerous auctions, an important site for early modern natural philosophy. In England, the earliest auctions took place in coffee houses in the City of London, the same places where the virtuosi gathered to conduct experiments.[51] Robert Hooke noted how he met friends and philosophical acquaintances at auctions, which he attended frequently, so that besides supplying philosophers with books and later specimens and instruments, auctions were an important place for encouraging sociability, that key ingredient in early modern

48 Patricia Fara, '"A treasure of hidden vertues": the attraction of magnetic marketing', *BJHS* (1995) 28, pp. 5–35, 16; Robert Boyle, 'An exact copy of the last will and testament of the honourable Robert Boyle', in *The Works of the Honourable Robert Boyle. In Six Volumes. To Which is Prefixed the Life of the Author*, ed. Thomas Birch, London, 1772, vol. 1, pp. clviii–clxxi, clx.

49 Alexander Gordon, 'John Horsley (1685–1732)', *Oxford Dictionary of National Biography*, vol. 9, pp. 1276–1277; Robert Schofield, *The Enlightenment of Joseph Priestley: A Study of His Life and Work from 1733 to 1773*, University Park: Pennsylvania State University Press, 1997, p. 142.

50 Martin Folkes, 'Some account of Mr. Leeuwenhoek's curious microscopes, lately presented to the Royal Society', *Philosophical Transactions* 32 (1722–1723), pp. 446–453, 447.

51 Larry Stewart, 'Other centres of calculation, or, where the Royal Society didn't count: commerce, coffee-houses and natural philosophy in early modern London', *BJHS* (1999) 32, pp. 133–153; Giles Mandelbrote, 'The organization of book auctions in late seventeenth-century London', in Robin Myers, Michael Harris and Giles Mandelbrote (eds.), *Under the Hammer: Book Auctions since the Seventeenth Century*, New Castle: Oak Knoll Press, 2001, pp. 15–36. For scientific auctions see Peter de Clercq, 'Private instrument collections sold at auction in London in the late 18th Century', *Bulletin of the Scientific Instrument Society* (2007) 95, pp. 28–36, and (2009) 100, pp. 27–35; John R. Millburn, *Retailer of the Sciences: Benjamin Martin's Scientific Instrument Catalogues, 1756–1782*, London: Vade-Mecum Press, 1986, pp. 72–88; J.M. Chalmers-Hunt, *Natural Historical Auctions 1700–1972: A Register of Sales in the British Isles*, London: Sotheby Parke Bernet, 1976.

science.[52] Auctions also transformed learning by making materials accessible to new classes. Cynthia Wall calls attention to the way auctions were held to be 'dismantling' aristocratic culture in the eighteenth century, breaking up the contents of great homes to redistribute them to a growing middle class.[53] Scientific auctions similarly dismantled learning, separating the collections of wealthy patrons and nobles to distribute materials to scholars and the enlightened public. The second-hand market thus had a significant impact on the demography of scientific inquiry in this period.

Preservation and repair

Once philosophers had obtained instruments and materials, they made an effort to keep them in good repair and prolong their useful life. This entailed techniques for preventing damage to apparatus, for preserving substances or, if artefacts were broken or 'injured', for repairing them. Maintenance could be carried out by philosophers themselves, or delegated to expert instrument-makers and artisans. Once again, domestic and artisanal techniques provided resources for these practices, which demanded both material and social judgements to undertake.

Methods for preventing damage included nealing, whereby ceramic chemical vessels such as crucibles were baked to prevent them from cracking. Robert Boyle thus spoke of vessels 'being first well neal'd to prevent cracking' before being used in experiments.[54] Boyle noted that the term came from 'Workmens language'.[55] Artisanal technique was thus judged reliable among scholars. Transporting instruments also demanded care. Goods were often damaged in transit, and there was little trust in porters. In eighteenth-century England, dealers told consumers of glassware to purchase 25 per cent excess to cover breakage.[56] Granville Wheler lamented that in shipping electrical equipment from Canterbury to London, 'the resin cakes must be packed up very carefully or they will suffer: mine do so very much in going up to London and returning'.[57]

The concern to prevent damage to instruments also influenced their design, and affected decisions over experimental agendas. Philosophers preferred robust, easily repairable instruments, and abandoned experiments if they threatened to damage the apparatus. In his version of the Torricellian experiment, Boyle noted that warming the air increased the height to which a column of mercury in a glass tube was raised, and yet,

52 Robert Hooke, *The Diary of Robert Hooke, 1672–1680*, ed. Henry W. Robinson and Walter Adams, London: Wykeham Publications Ltd, 1968, pp. 360–361, 414; Leona Rostenberg, *The Library of Robert Hooke: The Scientific Book Trade of Restoration England*, Santa Monica: Modoc Press, 1989, pp. 66–81.

53 Cynthia Wall, 'The English auction: narratives of dismantlings', *Eighteenth-Century Studies* (1997) 31, pp. 1–25.

54 Robert Boyle, 'A physico-chemical essay, containing an experiment with some considerations touching the differing parts and redintegration of salt-petre', in Boyle, op. cit. (20), pp. 129–158, 130.

55 Robert Boyle, 'An essay of the intestine motions of the particles of quiescent solids. Where the absolute rest of bodies is called in question', in Boyle, op. cit. (20), pp. 1–30, 24.

56 Maxine Berg, *Luxury and Pleasure in Eighteenth-Century Britain*, Oxford: Oxford University Press, 2005, p. 123; see also Sally Newcomb, *The World in a Crucible: Laboratory Practice and Geological Theory at the Beginning of Geology*, Boulder: Geological Society of America, 2009, p. 80.

57 Wheler quoted in Simon Schaffer, 'Experimenters' techniques, dyers' hands and the Electric Planetarium', *Isis* (1997) 88, pp. 456–483, 471.

he wrote, 'I made no doubt, that it might have been rais'd much higher, but I was unwilling by applying a less moderate heat to hazard the breaking of my Glasses, in the place I then was in, where such a mischance could scarce have been repair'd.'[58]

Philosophers also worked to preserve the substances used in experiments and instruments. Some described how chemicals could be recovered. Salt solutions could be evaporated to dryness for reuse. The apothecary Robert Dossie explained how the preparation of yellow poudre de chartreux entailed boiling antimony with a solution of alkaline salt and water – 'The same solution of alkaline salts, which was at first used, may, after the sulphur has precipitated from it, on its growing cold, be equally well used again as any fresh quantity.'[59] Chemists recycled liquids through distilling apparatus to improve their yield. Thus Pierre Joseph Macquer explained how, in the distilling of essential oils from plants,

> The same water may be used again, with advantage … because the oily and odorous particles, with which it is impregnated, joining with those afforded by the fresh plant, form larger *moleculae*, capable of uniting more easily, and emerging better from the water; and consequently they increase the quantity of Oil. Thus the same water may be always employed in new distillations; and, the oftener it is used, with the greater advantage may it be used again.[60]

Needless to say, instruments did break, and this led experimenters to consider their repair. Repair constituted one of the major constituents of artisanal labor in the seventeenth and eighteenth centuries. As Richard Dunn observes of a large collection of instrument-makers' bills from the turn of the nineteenth century, 'the bills do not just list the sale of new instruments … most of the entries are for the cleaning and repair of equipment'.[61] 'Makers' spent much time replacing worn parts, mending cracked glass or fragile components, cleaning lenses and lacquering wood. Trade cards announced this role. The card of John Oliver of Grub Street in London explained that he 'Makes and Repairs all sorts of Glaziers Plumbers Tools at the Lowest Prices'.[62] In the sciences, Galileo and James Watt are among the more celebrated figures who offered services repairing instruments.[63] Repair was also a significant object of philosophical inquiry, and natural philosophers sought to collect and communicate information on techniques.

58 Robert Boyle, *A continuation of New Experiments Physico-mechanical, Touching the Spring and Weight of the Air and their Effects*, London, 1669, p. 13. Boyle heated the air with hot iron or tongs held near the receiver of the air-pump, but 'without making it touch the Instrument, for fear of breaking it'. Robert Boyle, *Animadversions upon Mr. Hobbes's Problemata de vacuo*, London, 1674, p. 72. Investigating the claim that mixtures of water and nitre froze the water, Boyle used a weather-glass, removing it from cold water 'to avoid injuring the instrument'. Boyle, op. cit. (16), p. 595.

59 Dossie, op. cit. (36), p. 282.

60 Pierre Joseph Macquer, *Elements of the Theory and Practice of Chymistry*, 3 vols., London, 1758, vol. 2, p. 137.

61 Richard Dunn, 'Touching and cleaning: the routine work of an East London instrument supplier', *Bulletin of the Scientific Instrument Society* (2006) 89, pp. 21–26, 22.

62 British Museum, Sarah Banks collection of trade cards, Banks 66.35.

63 On Galileo see Matteo Valeriani, *Galileo: Engineer*, Dordrecht: Springer, 2010, pp. 23, 221. Watt adapted a flute as the handle for an auger; see Michael Wright, 'James Watt: musical instrument maker', *Galpin Society Journal* (2002), 55, pp. 104–129, 114.

Cements, or 'lutes' for fixing glass and ceramics, were often discussed by chemical philosophers.[64] Robert Boyle explained how linseed oil was used to make pastes for cementing broken pipes; he also described how to mend 'clefts and commisures' using paper, which absorbed water to swell up and fill holes. Leaks in ships could be stopped on the same principle using dried salt beef.[65]

It is often assumed that repair work was especially valued in the provinces, where, as A.D. Morrison-Low has recently argued in the case of nautical instruments, makers were fewer, instruments were rarer and skilled repairmen could make a good living maintaining instruments, especially in port towns where octants, sextants and compasses were often renovated and resold.[66] Similarly, the difficulty of procuring new instruments in the European colonies has been seen as prompting repair cultures and adaptability in colonial instruments.[67] Further studies are needed to examine such claims, allying as they do the old and used with the periphery and the new with the centre. It may be that repair and reuse were common everywhere, but were adjusted to local resources and possibilities.

Deciding when instruments needed repair was not a simple business, prompting disagreements between makers and users, narratives of heroic repair work, and regressive disputes over the competence of instrumental performances.[68] Philosophers traversed diverse sites and communities in pursuit of repairs. Robert Hooke ordered his servants to mend his clothes, or took them to a tailor to be repaired. He had a Mr Scarborough mend his chimney, and left jewellery and mathematical instruments for repairs with Mr Haux and the clockmaker Tompion.[69] In the following century, repair seems to have been a particular concern among electricians, whose apparatus included many items made of glass, an expensive commodity in the eighteenth century (a dozen quality drinking glasses could cost a week's wages for many people).[70] Thus Joseph Priestley, Tiberius Cavallo, Benjamin Wilson and other electricians agonized over the best ways to mend the glass of Leyden jars, which were liable to crack during electric discharges.[71] Wilson described how to use wax, resin, turpentine and olive oil to seal cracks in a Leyden jar, while the lecturer Cadogan Morgan advocated using lower

64 See, for example, Dossie, op. cit. (36), pp. 49–52; Sara Pennell, 'For a crack and a flaw despis'd': thinking about ceramic semi-durability and the "everyday" in early modern England', in Tara Hamling and Catherine Richardson (eds.), *Everyday Things: Medieval and Early Modern Material Culture*, Farnham: Ashgate, 2010, pp. 27–40, 36.

65 Robert Boyle, 'Essay X. Of men's great ignorance of the uses of natural things: or, that there is scarce any one thing in Nature, wherof the uses to human life are yet thoroughly understood', in *The Works of the Honourable Robert Boyle*, op. cit. (48), vol. 3, pp. 470–494.

66 Alison D. Morrison-Low, *Making Scientific Instruments in the Industrial Revolution*, Aldershot: Ashgate, 2007, pp. 75, 122, 170, 204, 266–267.

67 On colonial instrument-makers and repairs see Silvio A. Bedini, *Thinkers and Tinkers: Early American Men of Science*, New York: Scribners, 1975, pp. 184–204.

68 Simon Schaffer, 'Easily cracked: scientific instruments in states of disrepair', *Isis* (December 2011) 102(4), pp. 706–717.

69 Hooke, op. cit. (52), pp. 17, 144, 164, 239, 355.

70 Berg, op. cit. (56), pp. 125–126.

71 See, for example, Benjamin Wilson, 'New experiments upon the Leyden phial, respecting the termination of conductors', *Philosophical Transactions* (1778) 68, pp. 999–1012, 1011–1012.

charges in experiments to avoid this problem.[72] Alternatively, one could avoid using glass in the first place. Tiberius Cavallo communicated a method used by Beccaria to make coated electrics (glass coated with conductors such as tinfoil or gilt paper) without using glass. Beccaria melted a mixture of colophonium and powder of marble, which he poured over tinfoil and spread about with a hot iron, then covered with another sheet of tinfoil. Cavallo reckoned that this could be advantageous, 'if broken, it may be repaired by a hot iron; but glass, when broke, can never be repaired'.[73]

Finally, when instruments were damaged beyond repair the broken parts could still be reused for other purposes. Lavoisier proposed that to contain liquids for distillation, 'The best utensils for this purpose are made of the bottoms of glass retorts and matrasses.'[74] A heated iron ring connected to a wooden handle could be placed around the broken vessel to make it usable.[75] Priestley used pieces of broken crucibles to hold materials heated with a burning lens.[76]

The motivations for making do

Having established that natural philosophers engaged in practices of making do and the stewardship of objects, it is next necessary to ask why they did it. What were the motives for such practices among early modern scientific practitioners? To the degree that philosophical sites coincided with domestic spaces, they no doubt participated in the 'making do' of the early modern household. As Strasser notes, making do, stewardship and bricolage were a response to scarcity and the need to avoid expense. Natural philosophers suffered from both. They faced unique problems of scarcity because they dealt in rare or unusual materials. The French chemist Nicolas-Louis Vaquelin wrote that red lead, mined in Russia, had become 'exceedingly scarce ... it is sold at present for its weight in gold'.[77] Peter Simon Pallas added that 'it is difficult to procure the quantity necessary for experiments'.[78] The scarcity of specialized instruments also prompted concern. Uppsala's professor of chemistry Tobern Bergman complained that it was hard to find crucibles for precisely weighing substances because those commonly available 'have rough surfaces filled with little holes, which hide a quantity of the matter very considerable where experiments are made upon minute portions'.[79] Some claimed that distance from urban centres determined the need to make do. Discussing the use of rain gauges, the English agriculturalist William Marshall wrote that 'gentlemen who reside at a distance from the metropolis may find it difficult to procure a mathematical apparatus'

72 George Cadogan Morgan, *Lectures on Electricity*, 2 vols., Norwich, 1794, vol. 2, p. 460; see also George Adams, *An Essay on Electricity, Explaining the Principles of that Useful Science*, London, 1799, p. 271.

73 Tiberius Cavallo, *A Complete Treatise of Electricity in Theory and Practice*, London: E. & C. Dilly, 1777, p. 145.

74 Antoine-Laurent Lavoisier, *Elements of Chemistry* (tr. Robert Kerr), London, 1790, p. 377.

75 Lavoisier, op. cit. (74), p. 377.

76 Priestley, op. cit. (36), p. 22.

77 Nicolas-Louis Vaquelin, 'On the use of the new metal called chrome, the oxyd of chrome, and the chromic acid', *Philosophical Magazine* (1798) 2, pp. 74–77, 76.

78 Pallas, quoted in Vaquelin, op. cit. (77), p. 77.

79 Torbern Bergman, *Physical and Chemical Essays* (tr. Edward Cullen), London, 1788, vol. 2, p. 87.

and therefore might make their own gauges consisting 'of a common tin tunnel to collect the rain-water; a common glass bottle to receive it; and a small China vessel to measure it in'.[80]

Philosophers also had to trade the need for scarce materials and instruments off against the expense of obtaining them. They often mentioned trying to avoid high costs in their investigations. Joseph Priestley adapted kitchenware to chemical experiments on airs because, as he put it, this was good for 'keeping off such as would involve me in expense'.[81] Cavallo sought a substitute for glass in electrical apparatus as something which 'might answer better than glass for this purpose, [or] at least be cheaper'.[82] Making science appeal to the public also prompted authors to keep in mind the costs of experimenting. Speaking of the contents of a planned book on chemical theory, Boyle wrote, 'I declined several Experiments that required either more skill, or more time, or more expence than could be well expected from most Readers, and chose rather to employ such Experiments as may be more easily or cheaply tried.'[83] Similarly, Thomas Sherley prefaced the translation of a book of secrets of 1677,

> the Experiments here alledged, are so easily practicable, That a great part of them may be performed in a Chamber, (by such common and cheap means, as are constantly to be had, either at the Druggists, or common Chymists) and do not require a Specious [*sic*] Laboratory ... which is expensive.[84]

As in the case of repair, a concern over the expense of instruments could have consequences for experimental results. A striking instance of this is Priestley's work on dephlogisticated air. In early experiments, Priestley failed to produce dephlogisticated air from substances such as Roman vitriol, manganese, and green copperas by heating small quantities of material on quicksilver with a burning lens or in a gun barrel. He later generated the air successfully by heating substances in long retorts with their bellies immersed in sand and the necks in water or mercury. Priestley wrote that he had not discovered the better method out of a concern for economy. In the early experiments, he explained,

> I did, indeed, sometimes make use of a phial with a ground stopper and long tube; but this being an expensive instrument, I used it very rarely, and it was more liable to accidents than the long retorts, which are reasonably cheap, especially when made of green glass.[85]

80 William Marshall, 'Experiments and Observations concerning Agriculture and the Weather', *Critical Review: or, Annals of Literature* (1779) 48, pp. 444–453, 451.

81 Quoted in Crosland, op. cit. (35), p. 232; see also Lavoisier, op. cit. (74), p. 377.

82 Cavallo, op. cit. (73), p. 144.

83 Robert Boyle, *Advertisements about the Experiments and Notes Relating to Chymical Qualities*, London, 1675, p. 6.

84 Johann Sigismund Elsholtz, *The Curious Distillatory, or, The Art of Distilling Coloured Liquors, Spirits, Oyls, &c. from Vegitables, Animals, Minerals and Metals* (tr. Thomas Sherley), London, 1677, 'To the Reader'.

85 Joseph Priestley, *Experiments and Observations Relating to Various Branches of Natural Philosophy; with a Continuation of the Observations on Air*, London, 1779, pp. 202–203.

While the avoidance of expense was no doubt important to natural philosophers, another less obvious motivation for their stewardship may have been a sense of wonder at the inherent properties of materials, no doubt understood as divinely ordained. In his 1671 'Essay of Men's Great Ignorance of the Uses of Natural Things', Robert Boyle referred to practices of repair and adaptation as evincing the unexpected properties and uses of materials that might be gleaned by more systematic philosophical inquiries. Hence, 'Tobacco ... was suffered yearly to rot and perish like other herbs' while indigo 'would uselessly perish' until men discovered processes to make them into useful commodities. Other uses of materials produced wondrous effects, as when 'out of the skulls and bones of dead men ... chymists do ordinarily, to the wonder of the ignorant, draw store of spirit, and oil, and phlegm'. Boyle thought these techniques, producing 'considerable and unlikely effects', were 'strange' and pleasing.

Stewardship also manifested, no doubt, the widespread value of thrift among early moderns; that is, a concern for frugality, simplicity and the avoidance of waste, stemming from religious and moral grounds as much as from practical necessity. To define 'thrift' is not simple. The term changed its meanings over time, and it is outside the scope of this essay to follow those changes in detail, but since the time of Max Weber critics have shown how senses of thrift moved between a moral, ascetic restraint and a more economically minded concern for saving money and for careful expenditure.[86] Thrift could be negatively associated with miserliness or avarice, but more commonly it carried the positive connotation of diligence and temperance.[87] As Boyle wrote of his French master Marcombes, 'Thrifty he was extremely, and very skilful in the flights of thrift; but less out of avarice, than a just ambition, and not so much out of love to money, as a desire to live handsomly at last.'[88]

The career of Benjamin Franklin provides perhaps the clearest example of a philosopher concerned with thrift. Franklin's sense of thrift was rooted in his upbringing among New England Puritans, for whom thrift was a public aspiration to self-discipline and moral constraint.[89] Expressing what Stephen Innes called 'a secularized version of the Protestant ethic', Franklin sought to avoid the squandering of time and money in all areas of his life.[90] From the 1730s, he was also a Freemason, for whom restraint was similarly important: 'use the blessings of heaven with temperance and moderation', as

86 For the Boyle quotations see Boyle, op. cit. (65), pp. 486, 488–489. For the history of meanings of thrift see Peggy A. Knapp, 'Thrift', in Robert Edwards (ed.), *Art and Context in Late Medieval English Narrative: Essays in Honor of Robert Worth Frank, Jr*, Woodbridge: Boydell & Brewer Ltd, 1994, pp. 193–205; Joshua Yates and James Davison Hunter (eds.), *Thrift and Thriving in America: Capitalism and Moral Order from the Puritans to the Present*, Oxford: Oxford University Press, 2011; Max Weber, *The Protestant Ethic and the Spirit of Capitalism* (ed. Richard Swedberg), New York: Norton, 2008.

87 On Puritan notions of thrift see James Calvin Davis and Charles Mathewes, 'Saving grace and moral striving: thrift in Puritan theology', in Yates and Hunter, op. cit. (86), pp. 88–116; Karl. J. Weintraub, 'The Puritan ethic and Benjamin Franklin', *Journal of Religion* (1976) 56, pp. 223–237.

88 Robert Boyle, 'An account of Philaretus during his minority', in *The Works of the Honourable Robert Boyle*, op. cit. (48), vol. 1, pp. xii–xxvi.

89 On thrift among New England Puritans in Franklin's time see Stephen Innes, 'Thrift and prosperity', in Yates and Hunter, op. cit. (86), pp. 117–138.

90 Innes, op. cit. (89), p. 133.

one New England Mason put it.[91] Seeking to avoid excess and expense shaped Franklin's learning and his civic works. He often bought goods second-hand and valued the chance to borrow books from friends and acquaintances.[92] This desire to avoid buying new books led Franklin to establish Philadelphia's first library among his fellow members of the Junto, and following that he founded a popular subscription library which was copied throughout the United States.[93] Franklin also worked to bring order to the streets through the collection of waste. He carried out studies on efficient street-sweeping and introduced the first scavengers to Philadelphia, to pick up reusable materials.[94]

As he grew older, Franklin developed this thrift into what he called a 'philosophy of virtue' encouraging industry and frugality, both in himself and in others. 'Frugality' he defined as: 'Make no expense but to do good to others or yourself; i.e. waste nothing.'[95] Franklin exploited his skills as a printer to spread this philosophy abroad, printing proverbial sentences on thrift in his journal *Poor Richard's Almanack*, which he collated into a famous essay, 'The Way to Wealth', in 1757. Here he exhorted his audience not to waste money on superfluities: 'The Art of getting Riches consists very much in Thrift.'[96] Domestic thrift was thus conjoined with philosophy and with commerce, and Franklin's print shop, as an extension of his artisan household, was likewise a place of thrift. For example, his wife helped in the printing shop by 'purchasing old linen rags for the paper-makers'.[97] Franklin was also a keen accountant, urging the need for careful bookkeeping, since even a tiny profit or loss could quickly turn into a significant one. As Otto Sibum has shown, Franklin's bookkeeping habits extended through his moral life, his commercial transactions and his scientific inquiries. He kept careful accounts of his own virtues, entering dishonorable acts into a ledger which he made using a reusable ivory memorandum book written in pencil and rubbed out when necessary. He resolved arguments by drawing up a balance sheet of pros and cons, which he then matched and cancelled out until only one side predominated. To refine this method he proposed a more abstract 'moral or prudential algebra' which gave a weighting to the different arguments. As Sibum shows, Franklin approached electricity in the same quantitative way, treating a surplus of electricity in a body as a credit, and a deficit as a debit, termed plus or minus. Electrical theory became 'a bookkeeping problem that was to be solved algebraically'.[98] Household thrift thus extended into

91 Edward Bass, *The Character of the Beloved Disciple. A Sermon Preached before the Ancient and Honorable Society of Free and Accepted Masons at St. Paul's*, Newbury, MA, 1780, p. 30.

92 Benjamin Franklin, *Autobiography of Benjamin Franklin*, New York: Modern Library, 1944, pp. 10, 17, 50.

93 Franklin, op. cit. (92), pp. 87–89.

94 Franklin, op. cit. (92), pp. 140–142, 145.

95 Franklin, op. cit. (92), p. 94; Norman S. Fiering, 'Benjamin Franklin and the way to virtue', *American Quarterly* (1978) 30, pp. 199–223.

96 Franklin, op. cit. (92), p. 209.

97 Franklin, op. cit. (92), p. 90.

98 H. Otto Sibum, 'Nature's bookkeeper: Benjamin Franklin's electrical research and the development of experimental natural philosophy in the 18th Century', in J.A. Leo Lemay (ed.), *Reappraising Benjamin Franklin: A Bicentennial Perspective*, Newark: University of Delaware Press, 1993, pp. 221–246.

Franklin's artisanal and natural-philosophical endeavours, shaping his practice and his theories of nature.

Conclusion

The domestic and artisanal stewardship of objects, and making do, extended into the sciences in the early modern period, or at least into the chemical and physical investigations carried out in Britain and North America which have provided most of the focus here. Experimental settings were adapted from existing spaces such as the kitchen, the bedchamber or the cellar, while philosophers employed a range of skills and techniques to secure, maintain, repair and reuse scientific material culture. Drawing on domestic practice and artisanal know-how, they preserved and extended the lives of materials and instruments, motivated by practical necessity in a world of scarcity and expense, a moral and economical sense of thrift, and a desire to explore the degree to which the uses and lives of materials could be extended. The sum of these activities I have designated an early modern culture of 'recycling' in science, though it shared little with the logic of current environmental recycling. Nevertheless, practices of making do, stewardship and thrift remained important components of scientific inquiry during and well beyond the early modern era.

Indeed, contexts of scarcity have continued to prompt acts of making do since the end of the eighteenth century. In some respects, the rise of a consumer society in the later eighteenth century discouraged stewardship and making do, witnessed, for example, in the shift from durable pewter kitchenware to fashionable, but fragile, ceramics.[99] We should be wary, however, of assuming a drift towards some inevitable throwaway consumer society – in the same period building materials changed from wood to the more durable stone, and a thrifty concern for materials remained in the nineteenth century, so that figures such as Charles Babbage trumpeted the reuse of waste as a sign of progress and innovation.[100]

In the sciences, designated spaces and dedicated apparatus for experimental inquiry were beginning to become more common by the early nineteenth century, but natural philosophers still sought to encourage public engagement with science, and often did so by appealing to cheap and ready-to-hand apparatus. In 1830, Michael Faraday published *Chemical Manipulation*, a popular handbook of chemical techniques which included numerous tips on using kitchen utensils and household wares for experiments.[101] Like Priestley and Lavoisier, Faraday promoted the use of laboratory waste in experiments – 'very useful glass dishes and capsules are made out of old retorts, receivers, and flasks'.[102] But instruments should ideally be preserved as long as possible.

99 Pennell, op. cit. (64), pp. 31–32.
100 Charles Babbage, *Economy of Machines & Manufactures*, 3rd edn, London, 1846, pp. 6, 11–12, 393–396.
101 Michael Faraday, *Chemical Manipulation*, 3rd edn, London, 1842.
102 Faraday, op. cit. (101), p. 371.

Air-pumps, for example, could be kept under a tin cover when not in use, replacing worn silk valves when necessary.[103] The glass receiver should not be touched with glass or metal rods, nor laid down hastily on a table, in case it broke. Serious leaks 'should be sent to a workman to be repaired' and, 'When an instrument is absolutely bad, and cannot be replaced or repaired, the student must compensate ... by interposing a stop-cock between it and the retort, flask, or other vessel.'[104]

Faraday's book went through several editions in the nineteenth century, suggesting the continued relevance of making do in the laboratory. Indeed, professional scientists continued to be thrifty with materials even into the twentieth century. Ernest Rutherford and the Cavendish Laboratory in Cambridge were famous for their 'string and sealing wax' approach to experiment from the 1880s to the 1930s, using cheap materials to construct makeshift apparatus.[105] The physicist Wilfrid Bennett Lewis recalled that students at the Cavendish used outdated hand-operated tools to make their own instruments with 'bits of metal and wood that had been used and reused by generations of research students'. He reckoned that the experience was vital to technical breakthroughs such as radar in the Second World War, because, in wartime, 'Apparatus had to be put together with the materials available. Nothing could be wasted.'[106] After the war, this approach had some notable successes, but on the whole was taken to signal a decline in British science and engineering.[107]

Despite these instances, it has of course been the trajectory of research laboratories in the age of 'big science' to use increasingly specialized equipment and space, with a growing consumption of materials and energy. The switch from making do to more dedicated material culture and space in science warrants further investigation, but may have been partly a product of professionalization in the sciences in the nineteenth century. Today, research laboratories are considered some of the most extensive consumers of natural resources – 'laboratories typically consume 5 to 10 times more energy per square foot than do office buildings. And some specialty laboratories ... consume as much as 100 times the energy of a similarly sized institutional or commercial structure'.[108] The history of recycling in science may have value in the environmental management of such concerns. Recently, a new interest in sustainability in laboratories has arisen, with a growing demand for more careful stewardship in experimental settings. For example, a recent online manual on sustainable practice in science proposes

103 Faraday, op. cit. (101), p. 865.

104 Faraday, op. cit. (101), p. 863.

105 Alexander Wood, *The Cavendish Laboratory*, Cambridge: Cambridge University Press, 1946, p. 18; Stuart Blume, 'Whatever happened to the string and sealing wax?', in Robert Bud, Susan E. Cozzens and Roy F. Porter (eds.), *Invisible Connections: Instruments, Institutions and Science*, Bellingham: SPIE Optical Engineering Press, 1992, pp. 87–101.

106 Quoted in Ruth Fawcett, *Nuclear Pursuits: The Scientific Biography of Wilfrid Bennett Lewis*, Montreal: McGill-Queen's University Press, 1994, pp. 7, 26.

107 Francis Spufford, *Backroom Boys: The Secret Return of the British Boffin*, London: Faber and Faber, 2004.

108 US Environmental Protection Agency/US Department of Energy, *Laboratories for the 21st Century: An Introduction to Low-Energy Design*, Golden: National Renewable Energy Laboratory, 2008, p. 1.

that scientists should try to repair equipment themselves rather than assume it is terminally broken, they should donate excess chemicals and instruments to other scientists to avoid them being wasted, and they should reuse plastic and glassware whenever possible.[109] 'You may save money, time and materials', the website explains.[110] Franklin would surely have approved.

109 See the website of the University of California at Santa Barbara Laboratory Research and Technical Staff, http://sustainability.ucsb.edu/LARS, accessed 28 June 2011.

110 UCSB, op. cit. (109), http://sustainability.ucsb.edu/LARS/best_practices/electronics_apparatus/electronic_repairs.php, accessed 28 June 2011.