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The Contribution Good as the Foundation of the Industrial Revolution

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The Industrial Revolution emerged when research became collective, which is a transition that can be modelled using a contribution good model of technical change. The Industrial Revolution cannot readily be modelled if research is treated as a public, private or club good. Recent work on the knowledge commons and on 'network' and 'anti-rival' goods has offered more promising perspectives, but we have proposed that research is most suitably considered as a novel good, namely a 'contribution good.' A contribution good is a non-depletable good jointly available only to those who have contributed to its creation. Here we show that the Industrial Revolution, and some of the institutional developments that accompanied it, conform well with a contribution good model of technical change.

When individuals require access to the contributions of others before the costs of their own research activity can be recovered, a critical number of participants is necessary to establish a self-sustaining group. Before the number of contributors reaches that threshold, technical development and therefore economic growth are low; but after the number of contributors crosses that threshold, technical development and therefore economic growth rise dramatically. The Industrial Revolution represented a 50-fold acceleration in the long-term rates of economic growth, and the threshold characteristic of a contribution good model will account for that acceleration of long-term rates of economic growth.

A contribution good gives rise to a collective action problem that can be characterised as one of 'pure coordination.' The combined contributions of a sufficient

* We thank Professors Meir Kohn and John Scott of Dartmouth College for consistently invaluable advice; we thank Professor Emeritus Eric Jones for deep conversations; we thank Drs. Benjamin Powell, Robert Murphy and Vincent Geloso of Texas Technical University and Dr. Maria Pia Paganelli of Trinity University, TX, for key insights; we thank Dr. Patrick Michaels and Messrs. Andrew Forrester and Joseph Verruni of the Cato Institute for many helpful discussions; and we thank Professor David Edgerton and Dr. Thomas Kelsey of Kings College London for their shrewd and generous observations.

number will produce a result that no individual participant will regret. But confidence that others will take part is required to induce participation. Here we describe the institutions that, fuelling the Industrial Revolution, emerged to provide that pure coordination. Such institutions represented the voluntary association of researchers in contributing knowledge to each other and into a common pool.

The emergence of research institutions does not in itself confirm that the Industrial Revolution can be modelled using a contribution good model of technical change. Scholars of research have previously modelled research as fully non-excludable, and such scholars have posited the emergence of research institutions to foster knowledge commons as solutions to the collective action problems that consequently arise.

But if research institutions arose to address the problem of non-excludability, they would have institutionalised exclusion and punishment. If, on the other hand, research institutions had emerged to address the problem of a threshold or 'critical mass,' they would have institutionalised inclusion and pure coordination. Here we show that the research institutions of the Industrial Revolution indeed institutionalised inclusion and pure coordination, which reinforces the idea that the Industrial Revolution can be modelled using a contribution good model of technical change.

1.1 DEFINING THE INDUSTRIAL REVOLUTION

The Industrial Revolution represented the acceleration of economic growth, and to fully characterise that acceleration would require measuring GDP, and GDP per capita, over the millennia, which cannot easily be achieved. Yet it is generally understood that, before the demographic transition that followed on the Industrial Revolution, humanity inhabited a Malthusian world, where advances in GDP were largely translated into increases in population, which suggests we might use total population to proxy total GDP (Kirk 1996). In Gregory Clark's (2007: 32) words, "In the preindustrial world, sporadic technological advance produced people, not wealth."

Figure 1.1 summarises the total human population data since 10000 BCE as estimated from the archaeological and anthropological evidence by McEvedy and Jones (1978), and it shows that, between circa 5000–4000 BCE and circa 1500 CE, annual rates of global population growth averaged circa 0.04 per cent. At a first approximation, therefore, we can conclude that annual rates of GDP *in toto* growth were circa 0.04 per cent.

To look more closely at the British example, between 1250 and 1700 the population grew from circa 4.23 million to circa 5.20 million (Broadberry et al. 2015), which was an annual growth rate of 0.05 per cent, and though the growth was not smooth (Black Death 1349) that rate was comparable to that of previous centuries. The data in Figure 1.2 show, moreover, that between 1270 and 1650, with the exception of the

https://doi.org/10.1017/9781108692915.003 Published online by Cambridge University Press

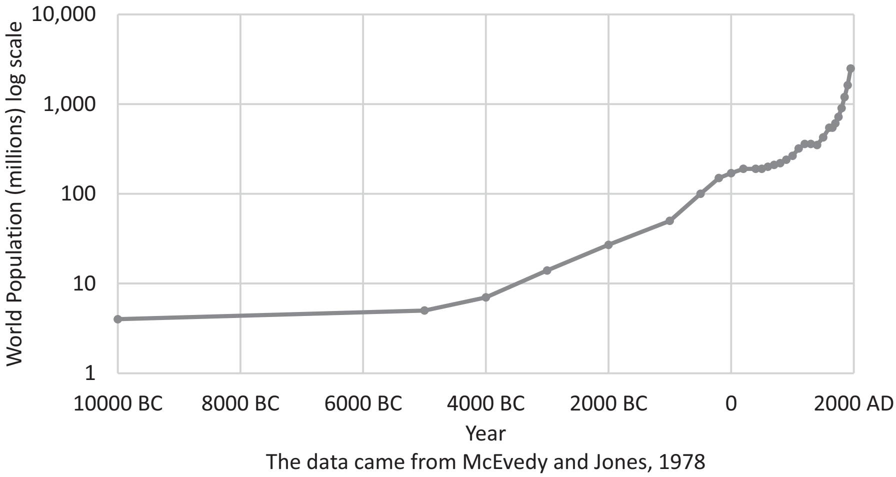

FIGURE 1.1. World population 10000 BC (BCE) to 1950 AD (CE) log scale

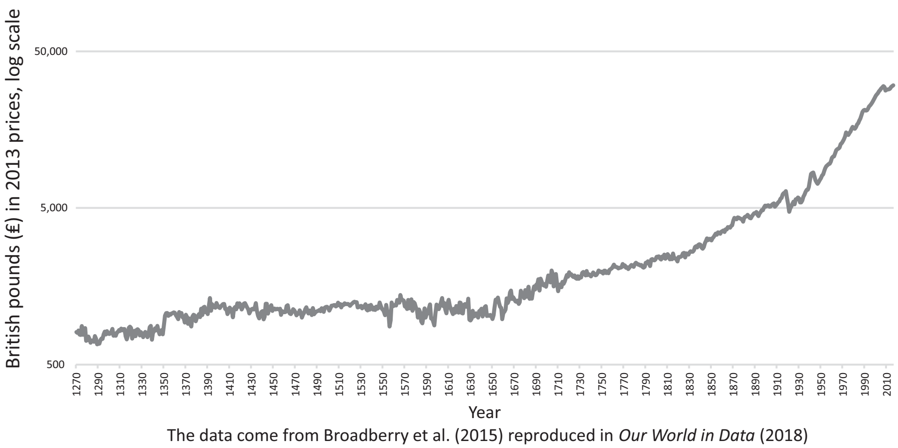

FIGURE 1.2. GDP per capita in England 1270–2016 log scale

Black Death years, GDP *per capita* growth rates in Britain were nugatory, which is also comparable with that of previous centuries.

After circa 1650, however, and coinciding with the increase in agricultural productivity per worker (Apostolides et al. 2008), the British growth rate in GDP *per capita* accelerated, eventually to achieve, around 1920, a long-term, sustained rate of circa 1.8 per cent PA. This is characteristic of the long-term growth rates of many lead countries, though by 1830 the USA had already attained its modern rates of GDP *per capita* growth of circa 2 per cent. GDP *per capita* is not, of course, synonymous with GDP *in toto* but, following a demographic transition, population

https://doi.org/10.1017/9781108692915.003 Published online by Cambridge University Press

growth is dwarfed by GDP growth, which allows here to define the Industrial Revolution as the process that started in the seventeenth century in England but which has since been transmitted to a number of other now-lead countries, whereby rates of economic growth increased circa 50-fold, from a rate of circa 0.04 per cent annually to a rate of circa 2 per cent annually.

1.2 MODELLING THE INDUSTRIAL REVOLUTION

1.2.1 *The Legacy of Nelson and Arrow*

The technical change that characterised the Industrial Revolution has not been modelled satisfactorily. Four of the great historians of the Industrial Revolution are Joel Mokyr, Deirdre McCloskey, Robert Allen and Eric Jones, and

- in Mokyr's words (2016: 6), scholars "know remarkably little about the kind of institutions that foster and stimulate technological progress and, more widely, intellectual innovation";
- in words from the subtitle of one of McCloskey's books (2010), "*Economics Cannot Explain the Modern World*";
- in Allen's words (2009: 3), "explaining the Industrial Revolution has been a long-standing problem in social science";
- and in Jones's words (2000: xx), explaining technological change is "something that is very hard to solve within the usual parameters of economics."

Two earlier significant scholars who studied the Industrial Revolution were Angus Maddison and David Landes, and

- in Maddison's words (1982: 56), "technical progress is the most essential characteristic of modern growth and the one that is the most difficult to quantify or explain";
- while in Landes's words (1969: 359), "it is impossible in the present state of our knowledge to evaluate the parameters of economic development."

These six scholars were articulating the lack of an economic model to account for the technical change that drove the Industrial Revolution. All six followed Solow (1957), as do we, in supposing that economic growth emerges by advances in knowledge, but all six were also aware of the conventional model for economic growth that was offered in their classic papers by Nelson (1959) and Arrow (1962), in which those two authors argued that research is a public good that would be underfunded privately and thus requires public subsidies. Yet the Industrial Revolution arose in Britain, and was relayed to the USA, both of which were largely *laissez faire* in research. In the words of Phyllis Deane (1979: 2): "The first industrial revolution occurred in Great Britain and is of particular interest in that it occurred spontaneously, without the government assistance that has been characteristic of most succeeding industrial revolutions."

As was also true of the USA. We have chronicled elsewhere the empirical evidence for research not needing government support (Kealey 2013) and we have also chronicled the failure of the conventional theoretical argument of knowledge being non-excludable (Kealey and Ricketts 2020).

1.2.1.1 Tacitness

Knowledge is of course non-rivalrous, but Nelson and Arrow had argued that knowledge is also non-excludable. But when their assertion that research is freely copied was tested in real life, it failed. When Mansfield et al. (1981) examined 48 products that had been copied within the major industries of New England during the 1970s, they reported the direct costs of copying were on average 65 per cent of the costs of innovation. A survey by Levin et al. (1987) of 650 Research and Development (R&D) managers provided similar results for the direct costs of industrial copying; and Mansfield et al. and Levin et al. reported that the marginal costs of copying were so high because the copiers had to rediscover for themselves the tacit knowledge embedded in the original innovation.

Mansfield et al. and Levin et al., however, had reported only the marginal costs of the actual copying; and Rosenberg (1980) and Cohen and Levinthal (1989) showed that companies seeking success in the market need first to sustain the fixed costs of a research staff whose activities are directed towards maintaining their own tacit expertise, which requires them to pursue active, and therefore expensive, research programmes, as fixed costs. Stigler (1961), moreover, has shown that companies also need to bear the costs of information, as well as the costs of failed imitation attempts. We may, therefore, not know for certain what the average costs of copying in industry are, but they appear to be so high that research, in industrial practice, is excludable in the sense that it is not available to free-riders. Any economic model for research must, therefore, accommodate the tacit nature of knowledge.

The fact that knowledge, including scientific and research knowledge, is tacit, was recognised from the outset of the enterprise of research: thus in 1543, in the two opening texts of the Scientific Revolution, Nicolaus Copernicus wrote in his *De revolutionibus* (1543) that he was writing only for those qualified to read it: "mathematics is written for mathematicians" (quoted in Shapin 1996: 122), while Vesalius dedicated the introduction to his *De humani corporis fabrica* to reiterating that only by working with their hands could physicians acquire useful knowledge. The following year, in a letter to Duke Albrecht of Prussia describing his discovery of the inclination of the compass, Georg Hartmann wrote, "I would right gladly explain to your Grace, as far as it can be done by writing, for such things are more easily shown by handling than by letter" (Hartmann 1943 [1544]).

Technological tacitness, too, has been long recognised, and in 1180, Gervase, on describing a vault in Canterbury Cathedral in his *Chronicle*, wrote that its rebuilding "will be better understood by inspection than by any description" (Erlande-Brandenburg 1995: 152). Similar statements continued to be made: Diderot wrote in the *Encyclopédie* (1751–1766) that "in all techniques, there are specific circumstances relating to the material, instruments and their manipulation that only experience teaches" (Mokyr 2002: 28); while in 1820, Richard Edgeworth (see also below) reiterated the role of tacitness in knowledge transfer when he recounted how, after he had been shown around the Soho and other Birmingham workshops, he had become: "intimately acquainted with many parts of practical mechanicks, which I could not otherwise have learned in many months" (Edgeworth 1844: 73).

It was Michael Polanyi, moreover, who noted in his *Personal Knowledge* that because of the tacitness of knowledge "we can know more than we can tell" (1958: 4), and who described "the ultimately tacit nature of all our knowledge" (1958: 95). For these reasons, therefore, we have generated a model for economic growth that recognises knowledge as tacit. That tacit character, in turn, provides a private incentive to do research, because only with that tacit knowledge will individuals be able to access, and thus exploit, the discoveries of others.

Being tacit, knowledge is therefore not a public good. But nor is it a private good in the sense of being rivalrous and conventionally excludable. Rather, it can be generated by voluntary institutions of coordination.

1.2.2 *A Contribution Good Model of Technical Change*

Suppose that the flow of results and ideas that make up 'research progress' at any point in time is related to the number of researchers (n) who are active. The private benefit net of costs (c) to each of these researchers might be written H(n) – c, where H(n) is assumed to increase with the number of active researchers. We call new scientific and technical knowledge emerging under these conditions a 'contribution good,' because its benefits are available only to those who have contributed by incurring the cost c and who have thus acquired the tacit knowledge by which to access the research of others.

As H(n) increases with the increase in the number of contributing researchers, so do the private benefits of using the collectively accessible knowledge created. We can envisage that, at low levels of n, this private pay-off is negative – the costs of participating in research outweigh the achievable private benefits. At some sufficiently large and 'critical' value of n (say n*), however, the net pay-off becomes positive, and new researchers will have a private incentive to both contribute to, and exploit, the collective flow of new knowledge.

Thus the Industrial Revolution can be modelled as a quantitative phenomenon, dependent on the numbers of researchers crossing a threshold. When the numbers of potential contributors fall below that threshold it is privately unprofitable to share knowledge ($c > H(n)$ for $0 < n < n^*$), but when the number of potential contributors exceeds a threshold, researchers will find it profitable to contribute ($c < H(n)$ for $n > n^*$), and thereafter the numbers of contributors will explode in size because, with each additional contributor, the value to all, including to pre-existing contributors, increases. Consequently, the growth in the community of researchers becomes self-sustaining – there is a 'take-off' – which will be sustained by new researchers contributing to and exploiting the collective flow of new knowledge.

It is this ability to provide a conceptual underpinning for a relatively abrupt historical transition from very low rates of productivity growth to higher and sustained levels that leads us to propose that a mechanism of this type lay behind the Industrial Revolution. And we are encouraged in the suggestion that the Industrial Revolution was primarily a quantitative rather than qualitative phenomenon by the conclusions of other scholars. Thus, Robert Allen (2009: 257) wrote:

> Eighteenth-century experimentalism was, therefore, not novel. It had precedents running back centuries. The difference between the eighteenth century and earlier periods was quantitative – an increase in the volume of experimenting – rather than qualitative.

If we follow Arthur (2009) in modelling growth as the consequence of a rearrangement of ideas, we can see how propitious the sharing of ideas can be. If 10 individuals, for example, each produce one idea, and if those 10 individuals each share their idea, then – for the cost of generating only one idea – each individual gets access to many potential combinations of new ideas. For example there will be $10!/(10-3)!3!$ or 120 possible combinations of 3 out of the 10 contributions, and 252 ways of combining 5 together. In total, 1,023 combinations of different sizes will be potentially available. Koppl et al. (2018) use this concept in their 'combinatorial model of world economic history' to show how the generation of successive ideas increases the value of the pre-existing ones in a process that generates exponential growth. Koppl et al. did not, however, describe human agency, and in this chapter we describe the institutional changes that accelerated the rate of exponential growth 50-fold in the process known as the Industrial Revolution.

It might seem that the joint use by researchers of the flow of new research developments means that our approach must have affinities with the Nelson/Arrow 'public goods' view of research. What distinguishes the two models is the assumed nature of the spillovers. In the public goods framework, the benefits from new knowledge are 'freely' available to all, while in the contribution good model they are available only to those who have made a contribution and have paid the cost c. Only by participation in the collective endeavour, and only by contributing new knowledge, can an individual gain the tacit knowledge by which to transfer the knowledge from the collective pool into their own profitable opportunities. Remodelling research as a contribution good, rather than as a public good, thus changes the game from a 'prisoner's dilemma' to one of 'pure coordination.'

There is no longer a free-rider problem but a 'critical mass' problem. The main fear on the part of participants is not that their ideas will be picked up and used by others, but that other potential contributors will not have the confidence to engage and will underestimate the private advantages that access to the collective resource will bring. This fear was articulated by Michael Polanyi (1962: 54):

> [C]onsider the effect which a complete isolation would have on the progress of science. Each scientist would go on for a while … but in the absence of further information about the results achieved by others, new problems of any value would cease to arise and scientific progress would come to a standstill.

So, researchers do research to acquire the tacit knowledge by which to access the research of others; and it's the hope of copying that *incentivises* research; it doesn't disincentivise it. Here we show – by quoting from a succession of observers who explained why they created such institutions – how the Industrial Revolution was characterised by the formation of institutions which, by implicitly recognising the special character of research as a 'contribution good,' were uniquely suitable for assembling a 'critical mass' of new knowledge. Such institutions were necessary because, as Michael Polanyi, noted in his *Personal Knowledge*, the tacitness of knowledge "restricts the range of diffusion to personal contacts" (1958: 55). As Thomas Spence asked during the 1770s, who is most likely to attain

> a distinct knowledge of any intricate subject, he who searches it by contemplation and the help of books only, or he who attends a well-regulated society, where the subject is freely debated as a question on both sides or demonstrated by the joint endeavours of the members?
>
> (Jackson 2019: 77)

Pure coordination is the solution to the collective action problem posed by the contribution good, namely achieving critical mass, and this chapter describes the emergence of the institutions that provided that pure coordination and thus facilitated the Industrial Revolution.

1.2.3 *Some Related Perspectives*

The contribution good framework shares some features of other approaches but differs from each in important respects.

Research as a Club Good. Problems of joint consumption can be addressed by private action through the establishment of clubs. Clubs form when exclusion mechanisms can be introduced at some economic cost and the 'club resource' – whether a golf course, swimming pool or local fishing ground – can be protected from 'free-riders.'

The evolution of club-like arrangements clearly plays a part in the history of the Industrial Revolution, but though a contribution good shares similarities with club

https://doi.org/10.1017/9781108692915.003 Published online by Cambridge University Press

goods, 'club like' resources are subject to potential crowding and 'over-use,' which is not the case for new knowledge and information: new club members in the contribution good framework automatically add to the joint pool of knowledge.

Research as a Network Good. Recent innovations have drawn attention to the role of network effects in raising productivity. A modern social media platform, for example, is more valuable to each user as the total number of users increases. The 'critical mass' idea that we use to explain the 'take-off' phase of the Industrial Revolution clearly has affinities with network externalities. Yet, though a contribution good shares similarities with network goods, Metcalfe's Law proposes in the case of telecommunications networks that the value of new knowledge rises exponentially with the number of contributors, while in Kealey and Ricketts (2014) existing researchers always benefit from newcomers but these additional researchers may make contributions of declining value.

Goods subject to strong network effects have been labelled 'anti-rival' (Weber 2004) on the grounds that additional users are welcome and do not harm incumbents. Clearly our 'contribution good' approach to science and research makes it 'anti-rival.' However, we dispute the widely accepted view that all anti-rival goods are non-excludable as well as non-rival, and that they are therefore types of public good. Because of the tacit nature of much new knowledge, spillovers of knowledge are in reality mainly confined to contributors, which therefore produces a different game theoretic structure from the usual prisoners' dilemma. In reality, non-contributors to knowledge will not benefit, and to that extent they are excluded – even if the incentives are such that contributions are eagerly sought and willingly supplied.

Research as an Outcome of Iterative Games. Solutions to free-rider problems have been proposed that rely on continued repetition of a game to induce cooperation. Where defection in a round (e.g. departing from the norms of 'openness' in pursuit of private gain) can be punished by future exclusion or loss of 'reputation,' it is possible to argue that institutions can evolve which embody the values of 'the republic of science.' This possibility is explored by Dasgupta and David (1994) – research results are shared amongst those who are deemed trustworthy and abide by the rules establishing recognition and priority – in the context of the development of pure science.

But whereas the evolution of institutions that secure the social benefits of openness in science is a common thread running between the repeated game approach and the contribution good framework, the former is focused on methods of exclusion as a response to the free-rider problem, while the latter is focused on securing coordinated engagement and the critical mass problem (see also below for a discussion on innovation commons).

Research in Endogenous Growth Theory. The difficulty of incorporating technical change into a model of growth without departing from the assumption of perfectly competitive 'price-taking' behaviour led to the explicit incorporation of market power into the analysis – for example, Paul Romer (1986, 1990). In Romer

https://doi.org/10.1017/9781108692915.003 Published online by Cambridge University Press

(1990: 84–85), patent rights in producer goods incorporating design improvements are secure and permit the receipt of streams of quasi rents. New knowledge is thus rendered partially excludable.

To the extent that Romer's model renders new knowledge partially excludable, it has similarities to the contribution good. But in Romer's model, knowledge is innately non-excludable and is rendered partially excludable only by virtue of government-supplied temporary legal monopolies; while under the contribution good model, new knowledge is innately tacit. Consequently, Romer's model seeks to resolve the collective action problem of non-excludability by positing the promotion of excludability, while under the contribution good model, the collective action problem of excludability is resolved by the creation of institutions of coordination. As we show here, the empirical history of the Industrial Revolution is of the creation of institutions of coordination, not of promoting excludability: indeed, a key characteristic of the Industrial Revolution was the move from secrecy to openness, in industrial as well as academic research. Moreover, there is no empirical evidence (outside of pharmaceuticals, which are a special case by virtue of the weight of government safety regulation) that patents do promote technical innovation (for a review of the literature, see van Gompel 2019: 878).

Research as an Innovation Commons. Innovation commons theorists subscribe to the Nelson/Arrow public good model of knowledge: "new information, being nonrivalrous and nonexcludable, has properties of a public good. Markets do not efficiently supply public goods" (Potts 2019: 7). But since empirical evidence shows that investments in research are undertaken privately, innovation commons theorists argue that researchers have solved the collective action problem by collaborating in ways similar to the ways players collaborate in the cooperative games that Ostrom and her colleagues described for the management of common pool resources (1990). Consequently, innovation commons theorists posit the institutionalisation of cooperative games within research societies. For example, Allen and Potts (2016: 1040) write: "As a collective action problem, the innovation problem can be re-diagnosed as one in which a community of interest – nominally the enthusiasts for the new technology – need to develop institutional rules of governance to enable them to effectively pool and contribute innovation resources."

1.3 GOVERNING SCIENCE AS CONTRIBUTION GOOD

The societies that arise to resolve (i) the collective action problem of an Ostromian common pool resource (which is rivalrous but non-excludable), (ii) an innovation commons problem (in which knowledge is modelled as non-rivalrous and non-excludable), and (iii) a contribution good problem (where knowledge is modelled as non-rivalrous but, by virtue of its tacitness, excludable) will share many features in common, but the first two will be characterised by the punishment, by exclusion, of rule-breakers, and this is not a prominent feature of science.

Research societies certainly have codes of conduct. The oldest surviving research society is the Royal Society of London (founded 1660) whose leading spirit was Robert Boyle, and in his *Sceptical Chymist* of 1661, Boyle required researchers to be "sober and modest men … diligent and judicious … drudges of industry" who would "avoid contumelious language" and who would criticise only a man's "observation, not his want of sincerity" (Shapin and Schaffer 1985).

Codes of conduct might be helpful in any institution which is looking to overcome some social dilemma – be it the encouragement of engagement and openness within the group (as in modelling research as a contribution good) or the restriction of information flows to those outside (as in modelling research as an innovation commons), so we cannot use standards of conduct to distinguish between societies that are responses to free-riding (as postulated in the case of innovation commons) versus those that are building networks to address critical mass (as postulated in the case of the contribution good).

Nor can we use friendship to distinguish between research institutions that arose to address (i) the common action problem of research as non-excludable and (ii) institutions that arose to coordinate the solution to research knowledge being tacit. Research societies can certainly be rooted in friendship, as was illustrated by the Lunar Society, created in 1765. The Society met regularly around Birmingham in the English midlands (the meetings were held when the moon was full, to allow the attendees to get home by its light) and amongst its regular attendees were its convener and early proselytiser of evolution Erasmus Darwin, the steam engine pioneers Matthew Boulton and James Watt, the chemists Joseph Priestley and James Keir, the pottery industrialist Josiah Wedgwood, and William Withering the research doctor (to say nothing of Benjamin Franklin when he was passing through).

Also amongst its regular attendees was the inventor Richard Edgeworth, who in his *Memoirs* of 1820 wrote how the "mutual intimacy" of its members, even as they competed as well as collaborated with each other, "has never been broken but by death" (Edgeworth 1844: 81). But friendship would surely be a useful feature of any society, whatever the reasons for its creation. Punishment, though, would not. Punishment is a feature of the cooperative games that characterise an innovation commons, yet the innovation commons theorists themselves acknowledge that "innovation commons tend to be rather poor at endogenously dealing with punishment and conflict" (Potts 2019: 126).

Exclusion as punishment is indeed rare in research. In 1785, for example, Erasmus Darwin falsely claimed the discovery of digitalis as a treatment for heart failure that had actually been made by a fellow Lunatic, William Withering. Withering rarely spoke socially to Darwin again, but the Society understood that punishment by exclusion was self-defeating, so it localised the rupture to the social interactions of the two principals to the argument. Darwin was not punished by exclusion from the Society.

The early Royal Society apparently excluded. Skinner (1969) has chronicled a long list of distinguished researchers who were apparently excluded from the early Royal Society,[1] but he explains that the very length of the list shows that those people were not excluded as punishments for behaving badly but simply because the Society was then run as a social club; and those 15 or so distinguished researchers were simply members of different research circles – only after Newton became president did the Society seek to become an all-inclusive professional body. Thereafter, the Society excluded only those who had nothing to contribute (i.e. persons who were not distinguished scientists), which was a pattern of exclusion not of exclusion-as-punishment (as prescribed by cooperative games) but, rather, of 'pre-exclusion' for having nothing to contribute – such persons were simply not elected to membership; as is compatible with the Royal Society being the institutionalisation of a contribution game.

We can, therefore, use the pattern of exclusion to confirm that research societies were indeed created to encourage participation rather than to control free-riding, as is revealed by the allocation of kudos, for the institutions of research do not punish those who extract maximum benefit from accessing the research of others – rather the contrary, for some of the most celebrated episodes in research emerged when individuals such as Newton, Darwin, Wallace, Einstein, Crick and Watson, while working as theorists, reinterpreted and built on the findings of others. Newton is admired, not deprecated, for having acknowledged that, "If I have seen further, it is because I have stood on the shoulders of giants."[2]

To conclude this section, therefore, the pattern of exclusion from research societies suggests they did not emerge to reinforce the governance of common pool resources nor the management of innovation commons but, rather, to facilitate the production of contribution good resources.

1.4 THE BRITISH INDUSTRIAL REVOLUTION IN RELATION TO THE COMMERCIAL AND SCIENTIFIC REVOLUTIONS

There seem to have been at least two, earlier, aborted proto-Industrial Revolutions. During the high medieval period, the Italians invented or adopted double-entry bookkeeping, premium insurance, cheques, bills of exchange, deposit banking, and patents, amongst other technological innovations (which included the optical lens), and those developments were, in aggregate, revolutionary (as has been recognised in the term 'Commercial Revolution'), for by 1450 Italian GDP per capita was double

[1] Amongst the early excluded persons were (notoriously) Thomas Hobbes, Josiah Pullen, Edmund Dickinson, Sir Robert Sibbald, Leonard Plukenet, Robert Morison, Thomas Sydenham, Sir Thomas Browne, Samuel Collins, Peter Barwick, Nathanial Hodges, Arthur Dacres, Richard Wiseman, Sir John Hinton and William Whiston. Women were also excluded, not being admitted as fellows until 1945.

[2] Even it was said ironically, as an attack on his frenemy the very short Robert Hooke.

that of England's; indeed, between 1350 and 1420 Italian GDP per capita grew at 0.8 per cent PA (Fouquet and Broadberry 2015). The Dutch, too, were to enjoy a Golden Age (GDP per capita growth rates of 1.3 per cent between 1505 and 1595; Fouquet and Broadberry 2015).

Those two proto-revolutionary periods were, however, not sustained; not because they proved to be innately unsustainable but because, as Kohn (2005) has shown, they were aborted by predation and violence. Yet these two earlier revolutionary periods illustrate that the iconic British Industrial Revolution should not be characterised as a happy coincidence of natural resources such as coal and iron ore but, rather, as the product of a British culture that seized on those natural resources as the most propitious routes to private and public enrichment.[3] The evolution of that culture, which was nascent in Italy 1350–1420, the Netherlands 1505–1595 and the UK 1650–, was to be described by Deirdre McCloskey in her trilogy as 'bourgeois,' and by Kohn as 'commercial,' and the purpose of this chapter is to illuminate the institutions by which that bourgeois, commercial culture effected the revolutionary creation of new technology and thus wealth.

In characterising the early institutions of the Scientific and Industrial Revolutions, we shall make little distinction between them. It is now usual to distinguish between pure and applied science, but it not clear that that distinction would have been very apparent to contemporaries. Thus, Pastorino (2017) has shown how Francis Bacon's elaboration of the scientific method was informed by his experience when, first as Solicitor General (1607–1613) and then as Attorney General (1613–1618), he acted as a patent examiner when England already enjoyed a culture of commercial invention and innovation, and which seems therefore to have coincided with – and perhaps have anticipated – the inauguration of more disinterested scientific enquiry. Moreover, England's earliest formal research institution, the Royal Society, was founded in 1660 to "improve the knowledge of natural things and all useful arts, Manufactures, Mechanic practices, Engynes and Inventions by Experiment," while the Society of Arts, to name another London research body, was founded in 1754 "to embolden enterprise, to enlarge science, to refine art, to improve manufacture and to extend our commerce." The early institutions of the British research, in short, seemed to make little distinction between pure and applied research, and Robert Allen (2009: 257) has noted how autonomous from basic science much Industrial Revolutionary technology was: "invention in metals and textiles was largely independent [of pure science]."

Nor do we make much distinction between scientific and commercial entrepreneurialism and innovation, for in the story Aristotle told of Thales, the iconic

[3] Thus Allen (2009) argues that the steam engine emerged in Britain only because coal was abundant, but Greener (2015) showed that Thomas Newcomen's early steam engines were fuelled by peat and turf, and that Newcomen moved to coal fuelling only opportunistically, not obligatorily.

https://doi.org/10.1017/9781108692915.003 Published online by Cambridge University Press

'first scientist' of the sixth century BCE, we can see that the entrepreneurial method of the market is indistinguishable from the entrepreneurial method of the scientist. In Book 1 of his *Politics*, section 1259a, Aristotle reported of Thales that

> from his knowledge of astronomy he had observed while it was still winter that there was going to be a large crop of olives, so he raised a small sum of money and paid round deposits for the whole of the olive presses on Miletus and Chios . . . when the season arrived, there was a sudden demand for a number of the presses [so] he realised a large sum of money, so proving that it was easy for philosophers to be rich if they chose.
>
> (Aristotle, Politics, Book 1, section 1259a)

A commercial culture, therefore, will facilitate the emergence of research. Yet in itself it will not foster an industrial revolution, and the contribution good framework suggests that, for most of human history, the 'critical mass' of research activity required for spontaneous commercially driven growth was not achieved; and our initial task is to investigate those institutional developments that ultimately permitted it to be approached and eventually surpassed.

Here we consider the many early research societies that were formed, often with aristocratic patronage, which made use of incentives that were not necessarily entirely commercial in nature but which would have enabled the wider dispersion of scientific and technical knowledge than had generally prevailed before. Take-off, however, required that McCloskey's bourgeois attitudes and Kohn's commercial attitudes had become sufficiently established for the profit opportunities latent in the growing pool of scientific knowledge to become the main motivating force. At a certain point the profit motive, combined with a large enough research community, gave rise to a spontaneous and cumulative increase in the rate of technical advance as more participants were attracted. After this 'take-off,' the competitive pursuit of innovation rents would itself create incentives to gain access to the ever-growing pool of knowledge and, within the 'contribution good' framework, would imply incentives actively to share knowledge. This 'post take-off' world, we argue, is characterised by a significant degree of 'collective invention' within and across industries. Moreover, we argue that the world today can still be described as a 'post take-off' world: the current Industrial Age is the seamless continuation of the Industrial Revolution.

Although we do not attempt precisely to identify the point at which the profit motive, combined with a large enough research community, gave rise to a spontaneous and cumulative increase in the rate of technical advance as more participants were attracted into research, we note that Derek de Solla Price (1963: 9) showed that the increase in scientific knowledge globally, as judged by the numbers of journals and by other quantitative measures, entered into its current rate of exponential growth, with a half-life of about 12.5 years, around 1750.

https://doi.org/10.1017/9781108692915.003 Published online by Cambridge University Press

Carol Shiue and Wolfgang Keller (2007), moreover, have shown that by 1750 Britain's economy was quantitatively unique: by 1750, Britain's markets – as judged by the co-movement of prices – not only performed stronger and were more integrated than hitherto, but they were also stronger and more integrated than anyone else's. David Landes (1998: 246) has described another unique aspect of the British (then English) economy: "[L]ocal tolls had largely disappeared by the fifteenth century; as a result they had the largest internal market in Europe." The British economy in 1750, in short, was stronger, more integrated, and larger than any the Western world had seen. It could thus support the quantitative phenomenon of a threshold that the contribution good demonstrates.[4]

It can be hard to disentangle the simultaneous actions of social from quantitative factors. Alan Macfarlane (1978: 268) for example noted:

> England was as "capitalist" in 1250 as it was in 1550 or 1750. That is to say, there was already a developed market, mobility of labour, land was treated as a commodity, and full private ownership as established, there was very considerable social and geographical mobility, a complete distinction between farm and family existed, and rational accounting and the profit motive were widespread.

Gregory Clark (2007) has asked, therefore, if England was as capitalist in 1250 as it was in 1750, why did the Industrial Revolution not happen then? The same question was posed, in a different form, by Bennet Woodcroft FRS, who between 1864 and 1876 had been the clerk to the commissioners of patents in Britain. Woodcroft had been puzzled by John Kay's invention, in 1733, of the flying shuttle, which though a technically trivial advance, was nonetheless of vast commercial significance. Why was it, Woodcraft asked, that weaving had been "performed for upwards of five thousand years, by millions of skilled workmen, without any improvement being made to expedite the operation, until the year 1733?" (Howes 2017a: 6)

The answer to these questions is at least in part social. Thus a clue is provided by John Kay's own life story: as a young man he was apprenticed to a reed-maker (reeds were loom combs), and he is said to have returned home only after a month,

[4] The dependence of research take-off on market size might help explain the sequential appearance of the different sciences. Thus (simplistically), reliable mathematics emerged in ancient Greece, physics in seventeenth-century Europe, chemistry and experimental industrial technology during the eighteenth century, and biology during the nineteenth century with the publication of Darwin's *The Origin of Species*. This progression seems not to track the innate difficulties of the different sciences (Newton's *Principia* is surely a harder read than Darwin's *The Origin of Species*) but, rather, their increasing complexity. The problems of complexity can be addressed, at least in part, by increasing the size of researchers' networks, which will expand their sources of information – witness Charles Darwin's dependence, when developing his idea of evolution by natural selection, on Lyell's *Principles of Geology*, Malthus's *Essay on the Principle of Population* and John Gould's taxonomy of the finches of the Galapagos Islands. It may, therefore, not be a coincidence that the emergence of the more complex sciences tracked with the increasing size of markets; and to the extent that industrial development depended on the more complex sciences, so the two phenomena may have fuelled each other.

https://doi.org/10.1017/9781108692915.003 Published online by Cambridge University Press

claiming to have already mastered the business (Lord 1903: 91). Whether the story was true or only apocryphal, that it could have been propagated speaks to the weakening of the guilds for, in earlier eras of monopoly capitalism, apprenticeships were enforced, and breaking them precluded any further involvement in the trade. But, dating from around 1500, in England and the Netherlands uniquely in Europe, monopoly capitalism gradually succumbed to competitive capitalism (Ogilvie 2014). In the words of the scholar who popularised the term 'Industrial Revolution,' Arnold Toynbee (1884): "The essence of the Industrial Revolution was the substitution of competition for the medieval regulations that had previously controlled the production and distribution of wealth."

Ogilvie (2014: 171) has noted that by 1733 the textile guilds had been so weakened in England that entry into weaving had been freed. Moreover, Ogilvie also noted that guilds had always arisen where markets had arisen, regardless of geography or culture; so, because English guilds were only emblematic of the way markets had been regulated for 5,000 years, we can see why the invention of the flying shuttle had to wait until 1733 in Britain.

But if the substitution of competition for medieval regulations is the essence of the Industrial Revolution, this chapter largely limits itself to the downstream event, namely the development of institutions implicitly aimed at solving the collective action problem of critical mass.

1.5 CHRONOLOGY OF THE BRITISH INDUSTRIAL REVOLUTION

England's first impactful contribution to research was William Gilbert's (1600) *De magnete* (Robert Norman's *Newe Attractive* of 1581 made less impact). It was from *De magnete* that we acquired the terms 'electric' and 'electricity,' and Gilbert advanced the science of navigation in important ways. And in his paper 'The origins of William Gilbert's scientific method,' Zilsel (1941) showed how Gilbert did it: for Gilbert, who was famously social, was embedded within a network of scientific friends with whom he exchanged information. So Gilbert learned that the compass worked at latitudes up to the 80th degree because "This our most famous Neptunus Francis Drake, and the other circumnavigator of the globe, Thomas Cavendish, have told and confirmed to me" (Zilsel 1941: 18). Zilsel showed, moreover, either directly or by inference, that the other English compass pioneers of the time were all Gilbert's friends.[5] Many of those pioneers were sailors, or they were gentlemen who, unusually for the era, were friendly with sailors; and Zilsel concluded that English research was facilitated by the breakdown of social barriers – as markets accelerated,

[5] The English compass pioneers included Edward Wright, Thomas Harriot, Robert Hues, Abraham Kendall, Thomas Blundeville and William Barlowe. William Gilbert's papers were lost in the Great Fire of London, so Zilsel could not prove directly that all the pioneers were friends with Gilbert: in some cases he inferred the friendship from circumstantial evidence.

https://doi.org/10.1017/9781108692915.003 Published online by Cambridge University Press

so gentlemen like Gilbert exchanged information with artisans, to enlarge the mass of researchers contributing into the common pool of knowledge.[6]

Gilbert's was only one of at least five distinct mathematical/geographical/navigational research circles in England: three were centred on Thomas Allen, Henry Briggs and John Dee, respectively (Cormack 1997: 127), while another was centred on Henry Percy (1564–1632), the ninth or 'Wizard' Earl of Northumberland.[7]

The best-known research circle may have been yet another, Mary Herbert's at Wilton House. Here, from Aubrey's *Brief Lives* (1669–1696), is a record of Wilton House in the final decades of the sixteenth century:

> In her time Wilton house was like a College, there were so many learned and ingeniose persons. She was the greatest patronesse of witt and learning of any lady in her time. She was a great chymist and spent yearly a great deale in that study. She kept for her laborator in the house Adrian Gilbert (vulgarly called Dr. Gilbert)[8] halfe brother to Sir Walter Ralegh, who was a great chymist … She also gave an honourable yearly pension to Dr. Thomas Mouffett, who hath writt a booke *De insectis*. Also one … Boston, a good chymist … At Wilton is a good library

Latham (2010: 14) moreover has shown that Mary Herbert was embedded in yet another research network, one of aristocratic ladies including Lady Margaret Hoby and Margaret Clifford, Countess of Cumberland.

These research circles may seem unexceptional to us today, but it was not then unusual for researchers to seek seclusion and excludability. Thus Francis Bacon wrote in 1603 in *Valerius Terminus*:

> The discretion anciently observed … of publishing part, and reserving part to a private succession, and of publishing in a manner whereby it shall not be to the capacity nor taste of all, but shall as it were single and adopt his reader, is not to be laid aside, both for the avoiding of abuse in the excluded, and the strengthening of affection in the admitted.
>
> (quoted in Howard 2004: 477)

And later, Bacon (1626: 215) was still writing that: "we have consultations, which of the inventions and experiences we have discovered shall be published, and which not; and take an oath of secrecy."

6 Zilsel's thesis is supported by the observation that, after having eschewed breakfast for a millennium on the grounds it was a meal fit only for manual labourers, during the later sixteenth century the English upper classes started to eat breakfast again; thus was one barrier between the classes broken down (Terence Kealey 2013: 13–15).

7 Percy's coterie included Nathanial Torporley and Nicholas Hill, but also Thomas Harriot, Robert Hues and Walter Warner, who were the "three Magi" whom Percy supported financially (Gordon Batho 2000: 31–32). Researchers like Harriot and Hues could move from one circle to another as the patterns of patronage shifted, thus diffusing information beyond individual circles in ways not dissimilar from those described by Mark Granovetter (1973).

8 No relation to William Gilbert.

Thus too, in 1610, did Galileo publish his discovery of the rings of Saturn as *smaismrmilmepetaleumibunenugttauiras*, which he only later revealed transcribed into *Alitissimum planetam tergeminum obervavi*, "I have observed the most distant planet to have a triple form" (Reeves 1999). In 1656, to quote another example of secrecy, the Dutch scientist Christiaan Huygens published his discovery of the ring-like nature of Saturn's satellites as the anagram *aaaaaaacccccdeeeeehiiiiiiillllmmnnnnnnnnnooooppqrrstttttuuuuu*, "Saturn is encircled by a thin, flat ring, nowhere touching, inclined to the ecliptic" (Howard 2004: 485). While in 1660, in a further example of exclusion, Robert Hooke published his law of elasticity as *ceiiinosssttuv* (for *ut tension sic vis*; stress is proportional to strain) (Brown and Slawinski 2017: 110). Other researchers might lodge their findings with a lawyer or university, to reveal them and thus claim priority only when a later competitive publication arose.

Yet the same Robert Hooke who in 1660 had published his Law as an anagram, was one of the founders in that same year of the Royal Society in London, and in 1666 Hooke explained why research needed institutions like the Royal Society: it was to shift researchers away from the very culture of secrecy, atomisation and Intellectual Property rights (IPR) he had himself so recently embodied:

> There hath not been wanting in all ages and places great numbers of men whose genius and constitution hath inclined them to delight in the inquiry into the nature and causes of things ... But their Indeavours having been only single ... have ended only in some small inconsiderable product.
>
> (quoted in Mokyr 2002: vii)

Hooke was saying, in short, that when researchers' "Indeavours" were "only single," they "ended only in some small inconsiderable product," which, in the model of research as a contribution good sketched briefly above, can be represented as $c > H(1)$, where c is the private cost to a player of doing research, and where $H(1)$ is the private value of only one researcher's research (which, when researchers' "Indeavours" were "only single," was their own).

Hooke argued that collectivisation was the research way forward, and reinforcing that collaborative message Thomas Sprat, in his official *History of the Royal Society* published in 1667, condemned individual "pride, and the lofty conceit of men's own wisdom." Truth, he said, could advance only through the collective and "unanimous advancement of the same works" (Sprat 1667: 428). That is, research advanced best when organised collectively, which can be modelled as $c < H(n)$, where c remains the private cost to a researcher of doing research, and where $H(n)$ is the private value to a researcher of accessing the research of all researchers including their own.

And the transition from discreet to open knowledge was also seen in for-profit sphere; to quote Anton Howes (2017b: 12):

> Ralph Rabbards, in a 1574 list of inventions sent to Queen Elizabeth I, promised to reveal the details only in exchange for a "small chardge." Hugh Plat, writing in 1592, would do exactly the same, offering inventions that "the author proposed to disclose upon reasonable considerations." From the late sixteenth century, however, this reticence to share gave way to a culture of openness, sharing and even active evangelism.

We can represent the Royal Society as the institutionalisation of the informal circles (including the "invisible college" of which Robert Boyle wrote in 1646–1647; Purver 1967: 64) that had characterised English research since the latter decades of the sixteenth century. Amongst later societies was the Lunar Society (created in 1765 as noted earlier), which the inventor Richard Edgeworth had described in his *Memoirs* of 1820. He also described how a similar collection of researchers met regularly, first at Jack's and then at Young Slaughter's Coffee House in London.[9] Edgeworth described how such luminaries could be persuaded to share their advances with each other. It wasn't just to enjoy the excitement of "the first hints of discoveries, the current observations, and the mutual collision of ideas." It was also because "the knowledge of each member of such a society becomes in time disseminated through the whole body, and (. . .) combines the talents of numbers to forward the ideas of a single person" (Edgeworth 1844: 82–83).

Edgeworth was saying, therefore, that even competitors – especially competitors – benefitted from sharing their advances with each other, because such sharing "combines the talents of numbers to forward the ideas of a single person," thus echoing Hooke's lament that when researchers' "Indeavours" were "only single," they "ended only in some small inconsiderable product," and thus anticipating Kealey and Ricketts's (2014) model of a contribution good by which researchers, on contributing into a common pool of knowledge, increase the return on c from H(1) to H(n).

A later industrialist whose words echoed Hooke's and Edgeworth's was Gerard Muntz, the British steel maker, who in 1909 explained that his industry had created the Institute of Metals because:

> Each individual has some cherished bit of knowledge, some trade secret which he hoards carefully. Perhaps by sharing it with others he *might* impart useful information; but by an open discussion and interchange he would, almost for certain, learn a dozen things in exchange for the one given away. General increase of knowledge would give general improved practice.[10]

[9] This latter group included John Hunter the surgeon; Sir Joseph Banks, the President of the Royal Society; Daniel Solander, the follower of Linnaeus; Sir Charles Blagden, the Secretary of the Royal Society; Dr. George Fordyce FRS, the colleague of John Hunter; Nevil Maskelyne, the Astronomer Royal; Captain Cook; Sir George Shuckburgh the polymath; John Smeaton, the engineer; and Jesse Ramsden the instrument maker.

[10] "Institute of Metals Annual General Meeting in London." *Page's Weekly* 14: 160–162, 22 January 1909.

https://doi.org/10.1017/9781108692915.003 Published online by Cambridge University Press

Muntz was saying that once researchers pool their knowledge, an individual – on disclosing a first-mover discovery – would receive, in return, information on many others' first-mover discoveries, one or more of which he or she might then exploit as a second-mover advantage. And in his phrase "learn a dozen things in exchange for the one given away," Muntz was echoing Edgeworth's "combines the talents of numbers to forward the ideas of a single person," and Hooke's lament about single 'indeavours' ending "only in some small inconsiderable product." The incentives for researchers to share knowledge have thus characterised the Scientific and Industrial Revolutions since their inaugurations.

The contribution good, moreover, explains why researchers are incentivised to do their own first-mover research, because without it they cannot obtain the second-mover advantage of accessing the first-mover research of the other members of the research society. In his review of the British Agricultural Revolution of the eighteenth century, Eric Jones (1981) wrote that "the central puzzle is the emergence of the British taste for . . . agricultural improvements." The contribution good solves that puzzle, because without their own involvement in agricultural R&D ("improvements"), British farmers would not be able to access the advances of others.

On studying the development of steel in Britain during the nineteenth century, when that country dominated the industry and when men like Muntz were influential, Robert Allen (1983) systematised such chains of second-mover advantages into a model by which trade-offs from disclosing first-mover discoveries for second-mover opportunities were so mutually beneficial that collective invention became, to a remarkable degree, the dominant form of invention: "if a firm constructed a new plant of novel design and that plant proved to have lower costs than other plants, these facts were made available to other firms." The extent of research cooperation between Industrial Revolutionary firms was dramatic, and firms would even research their competitors' factories: thus one British steel master, Bell, reported that another, Vaughan, "let him measure the thermal characteristics of his [Vaughan's] 75 feet furnaces built in 1862."

Allen, moreover, found that collective invention still underpins the modern economy:

> [R]ecent engineering literature indicates such behaviour [collective invention] is rampant today. To the degree that economists have considered this behaviour at all, it has been regarded as an undesired 'leakage' that reduces the incentives to invent. That firms desire such behaviour and that it increases the rate of invention by allowing cumulative advance are possibilities not yet explored. They should be.
>
> (Allen 1983: 21)

Indeed. So Thomas Allen (1983) found in an international survey of 102 firms that no fewer than 23 per cent of their important innovations came from swapping information with their rivals: "managers approached apparently competing firms in other countries directly and were provided with surprisingly free access to their

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technology." While von Hippel (1998), in a survey of 11 steel companies in the USA, showed that 10 of them regularly swapped proprietary information.

John Scott (1996) has reported, moreover, in a study on cooperative research to reduce toxic air emissions, that:

> the cooperative R&D ventures do not appear to be a way for companies to avoid Schumpeterian competitive pressures that stimulate R&D investment. New, primary data at the disaggregated level of a particular type of R&D for particular companies support the belief that cooperative R&D ventures among manufacturing companies may well promote economic efficiency.

And Albert Link and Laura Bauer (1989), in their survey of cooperative research in US manufacturing, have confirmed it continues to drive economic growth and corporate profits. The patent data, moreover, confirms the importance of connectivity to innovation: thus Jaffe et al. (1993) showed that US patent citations were three to four times more likely to come from the same state as the originating patents, while Agrawal et al. (2008) not only confirmed that co-location promoted knowledge flow between inventors (by 24 per cent, correcting for ethnicity), but so too did co-ethnicity (by 14 per cent, correcting for proximity). Bailey et al. (2018) found that social connectiveness between US counties, as judged by the frequency of Facebook ties between counties, and after correcting for technology class and geographic distance, predicts the probability of cross-county patent citations. Mansfield (1995: 59), moreover, on looking at 66 examples of industrial–university links in the USA, found that "holding faculty quality constant, the probability of a firm supporting research at a college or university less than 100 miles away tends to be several times as great as the probability that it will support this research at a college or university 1,000 or more miles away."

Emphasising the role of connectivity in innovation, Dudley (2016) has argued that the clustering of important innovations between 1700 and 1850 in England, New England, and France, speaks to the UK and France preceding, by a century, other countries' adoptions of standardised national languages. Meanwhile, reporting on a natural experiment in connectivity, Burchardi and Hassan (2011) found that West German households and West German regions that had personal links to East Germany before the fall of the Berlin Wall in 1989 enjoyed, after the fall of the Wall, greater rates of economic growth than did West German families and regions that had fewer of those personal links; Burchardi and Hassan argued that that difference was attributable to West German entities converting their links into cooperative entrepreneurial opportunities.

The Industrial Revolution represented, we suggest, the outcome of a more collaborative and open approach to the development of new ideas of potential commercial value, as was exemplified in England by the evolution of the terms "chemistry" and "alchemy."

References to alchemists can be found as early as the fourteenth century in English literature (Linden 1974), and the early scientific giants respected the alchemists for being experimenters. Thus in 1623 Bacon wrote that: "I should call in some alchemist to help me; one of those who advise the studious to sell their books and build furnaces [i.e., laboratories]" (quoted in Linden 1974: 552), while in his *Sceptical Chymist* of 1661, Boyle also praised the experiments of the "alchemists" (West 1961: 106). Newton also admired the alchemists' experiments for, as Maynard Keynes reported, Newton was as much an alchemist as a physicist:

> Newton was not the first of the age of reason. He was the last of the magicians, the last of the Babylonians and Sumerians, the last great mind which looked upon the visible and intellectual world with the same eyes as those who began to build our intellectual inheritance rather less than 10,000 years ago.
>
> (Fanning 2009: xiv)

But the reverse of the alchemists' experimental coin was that they were secretive.

Newman and Principe (1998) have shown that the terms 'chemistry' and 'alchemy' were synonymous until the late seventeenth century, but that thereafter the discipline was to divide into two parts: the term "chemistry" was to be bestowed on that part that became open, whereas "alchemy" was to be bestowed on that part that remained, in the 1675 words of Nicholas Lemery, "in shadows" (Newman and Principe 1998: 61.) And in reflection of the shift of culture towards openness during the seventeenth century, the term 'alchemy' became derogatory. Thus William Gilbert in 1600 criticised alchemists for "veiling things in darkness and obscurity by means of silly words" (Zilsel 1941: 25), Bacon in 1605 condemned those who "sought to veil over and conceal by enigmatic writings" (quoted in Linden 1974: 552), and in 1661 Boyle denounced the alchemists for their "aenigmatical ... cloudy expressions," their "intolerable ambiguity," and their "abuse [of] words" to keep their research secretive (West 1961: 108).

It was in further reflection of the shift towards openness during the seventeenth century that Bacon defended grants of patents, not because he approved of monopolies, but because they enforced disclosure: "No discovery should be sanctioned save that it be put in writing. Only when that becomes standard practice, with experience at last becoming literate, should we hope for better things" (Pastorino 2017: 765).

1.6 HOW WIDESPREAD WAS COLLECTIVE INVENTION?

In a 1755 publication, *Histoire et secret de la peinture en cire*, Diderot reported that the mechanical invention of his day was collective (Hilaire-Pérez 2002). Mokyr (2009: 81), however, denies that collective research was an important feature of

https://doi.org/10.1017/9781108692915.003 Published online by Cambridge University Press

the Industrial Revolution, writing that it seems to have been limited only to three examples, namely the case of the Cleveland steel industry described by Allen (above), the case of the English clock and instrument manufacturers (below), and the case of the early high-pressure steam engine in Cornwall after 1800 (below).

MacLeod has described the case of the English clock and instrument makers:

> The Clockmakers and Spectacle Makers Companies retained an active control into at least the second quarter of the eighteenth century that included an inveterate opposition to patents. The members, meanwhile, were consistently improving the standards of their wares though the steady accretion of skills and ingenuity, and in cooperation with scientific investigators who were also their most exacting customers. New types of microscope were invented, new standards of accuracy achieved in astronomical and surveying instruments, and a variety of scientific instruments developed, notably the thermometer and barometer. English clocks and watches were justly famous. This was one area where Campbell had to acknowledge no Continental superiority or contribution (. . .)
>
> The Clockmakers ... spent over £500 to defeat 3 patents and 2 Acts between 1688 and 1718 (. . .)
>
> . . . with the argument that they [patents and Acts] restricted the free exercise of a skill whose development had always depended on small improvements, freely exchanged among craftsmen.
>
> (MacLeod 1998: 112, 113, 188)

With the consequence, in Adam Smith's words (1910: 224–225), that a watch that "about the middle of the last century could have been bought for twenty pounds, may now perhaps be had for twenty shillings [i.e., a twentieth of the price]."

Nuvolari (2004) has described the development by collective invention of high-pressure steam engines in Cornwall. Watt's patent had aroused such frustration that, after its expiry in 1800, the engineering community in Cornwall (then a major centre of mining) adopted a collective ethos of cooperative research. This was coordinated by Joel Lean, who launched a monthly newsletter *Lean's Engine Reporter* that, between 1810 and 1904, circulated individual engineers' advances, which helped raise the so-called duty or efficiency of the engines from 20 to 90 million pounds between 1810 and 1840. The engineers' cooperation was supported by the investors, one of the most prominent of whom, John Taylor, explained in 1830 why most investors supported a number of different engineers: "We [investors] are not the partisans of any individual engineer or engine maker; we avail ourselves of the assistance of many" (quoted in Nuvolari 2004).

Despite suggesting collective invention was rare, Mokyr (2009: 82) nonetheless concedes there was "a great deal of cooperation in the generation of technological progress," and we would argue that such cooperation is synonymous with technological progress being modellable as a contribution good. Bessen and Nuvolari

https://doi.org/10.1017/9781108692915.003 Published online by Cambridge University Press

(2016), who have catalogued a large number of advances made by mutual contribution, make no substantial distinction between collective invention and research collaboration.[11]

Initially, the acceleration of exponential industrial revolutionary research was incubated within individual industries, but the novel technologies then fructified other industries (the textile industry was revolutionised by watchmakers, who supplied gears and precision in part-making; while watchmaking itself had earlier been revolutionised by its meeting the needs of navigation; Allen 2009: 204), and as successive industries embarked on their accelerated exponential research expansions, so the whole economy was modernised not just by skilled craftsmen but also by entrepreneurial researchers expanding into fresh industries in a new *modus operandi*. Indeed, in his review of 1,452 innovators in Britain between 1547 and

[11] Amongst the examples of successful advances by mutual contribution cited by Bessen and Nuvolari (2016) were (1) the development of the *fluyt* (the favourite cargo ship of the Dutch East India company during the seventeenth century); (2) the eclipse during the eighteenth century of the London silk industry (which was characterised by secrecy and patents), by the Lyonnaise silk industry (where innovation was collective); (3) the introduction of wind power on a massive scale for the first time during the seventeenth century by the Zankstreet millwrights in the Netherlands; (4) the development of coal-burning houses in London during the seventeenth century; (5) the adoption of clover, sainfoin and turnips in crop rotations by open field farmers (which was against a long background in the UK of the sharing of agricultural knowledge, as embodied in such institutions as the Highland and Agricultural Society of Scotland (1785) or the Royal Agricultural Society of England (1830), and facilitated by such proselytisers as Arthur Young (1741–1820) whose *Farmer's Kalendar* went into its 215th edition in 1862) and which mirrored the culture of knowledge sharing amongst American farmers during the nineteenth and the early twentieth centuries, as evidenced by the fostering by the American Rose Society of the successful sharing of knowledge amongst breeders, and as evidenced by Faber's (1931) book *Cooperation in Danish Agriculture* reporting how Danish farmers formalised the sharing of knowledge by establishing 'control societies'; (6) the improvements in James Hargreaves's spinning jenny; (7) the development of high-pressure steam engines for western steamboats in the USA, which led to the greatest rate of transport productivity growth of the period; (8) the development of the early cotton industry in the USA as led by William Gilmour; (9) the development of 'Viennese chairs' during the nineteenth century; (10) the sharing of knowledge amongst the successful paper makers in Berkshire, Massachusetts, and amongst the early cotton manufacturers in Industrial Revolutionary Rockdale, Pennsylvania; (11) the Sewing Machine Combination or patent pool, which was created in 1856 when the four leading manufacturers, Singer, Wheeler & Wilson, Grover and Baker agreed to pool their patents but not to enforce them, so they shared their advances with each other – a similar example of such sharing was the semi-automatic cross-licensing and knowledge sharing in American railways during the nineteenth century; (12) the Bessemer Association or patent pool, which promoted collective invention in American steel production, with consequent dramatic increases in production; the sharing of knowledge was led by Alexander Holley, who was also the president of the American Institute of Mining Engineers, the vice president of the American Society of Civil Engineers and a founder of the American Society of Mechanical Engineers; and to promote the sharing of commercially important knowledge, the institutes with which Holley was associated published journals such as the *Transactions of the American Institute of Mining Engineers* or the *Transactions of the American Society of Mechanical Engineers* or the *Journal of the United States Association of Charcoal Iron Workers*.

1851, Anton Howes (2017a) showed that most of them improved more than one industry, and that 34 per cent of them improved industries for which they lacked relevant training, thus suggesting that entrepreneurs had learned to exploit the operation of contribution goods in themselves, regardless of the industry in which they were rooted.

Howes has also shown how the Industrial Revolutionary innovators acquired, by personal contact with each other, the very propensity to innovate: Charles Darwin may have shown in his *Descent of Man, and Selection in Relation to Sex* (1871) how human creativity had evolved by sexual selection, and Baumol (1990) may have shown how such creativity can be channelled into entrepreneurial activity, but Howes showed how that latent creativity could be honed by the institutions and societies to which individuals were exposed. The universities of Edinburgh and Leiden, for example, were much more innovatory in their cultures and produced many more innovatory graduates than did otherwise comparable universities. Similar observations can be made today, and Bell et al. (2019: 648) have shown how individual Americans' propensity to invent depends on "role-model or network effects" rather than on general levels of education.

During the Industrial Revolution, engineers across different industries proved very collaborative in their R&D, as was witnessed in Britain by the proliferation of engineering institutes, which included the Institute of Civil Engineers (1818), the Institute of Mechanical Engineers (1847), the Federated Institute of Mining Engineers (1850), the North of England Institute of Mining and Mechanical Engineers (1851), the Society of Engineers (1854), the Scottish Institution of Shipbuilders and Engineers (1860), the Institution of Naval Architects (1860), the Surveyors Institution (1868), the Iron and Steel Institute (1869), the Institute of Electrical Engineers (1871), the Institute of Municipal Engineers (1873), the Institute of Marine Engineers (1889), the Institute of Mining and Metallurgy (1892), the Institute of Sanitary Engineers (1895), the Institute of Water Engineers (1896), the Institute of Heating and Ventilating Engineers (1897), the Institute of Refrigeration (1900), the Institute of Metals (1908), the Institute of Concrete Engineers (1908) and the Institute of Foundry Engineers (1912) (Inkster 1991: 108). These institutes, like the American ones, organised meetings and published journals and newsletters.

In addition to the societies and institutions mentioned above, Britain witnessed the founding of a further cohort of industrial research societies including the Dublin Philosophical Society (founded in 1683), the Gentlemen's Society of Spalding in south Lincolnshire (1710; Isaac Newton was a member), the Dublin Society for Improving Husbandry, Manufactures and other Useful Arts (1731), the Royal Society of Edinburgh (1737), the Edinburgh Society for Encouraging Arts, Sciences, Manufactures and Agriculture in Scotland (1755), the Society of Civil Engineers (founded by Smeaton in 1771), the Derby Philosophical Society (founded in 1784 and immortalised by Wright's paintings), the Royal Irish Academy

(1785; focused primarily on the sciences), the Newcastle Literary and Philosophical Society (1793, initially for mining research), Anderson's Institution in Glasgow (1796), the Pneumatic Institution in Bristol (1799), the Royal Institution in London (1799), the Geological Society of London (1808, "for public improvement and utility," i.e. mining), and the Institution of Royal Engineers (1818, despite the name a civil body).

The Scottish enlightenment, where scholars, engineers and doctors came together to share knowledge (Adam Smith's executors were a chemist, Joseph Black, and a geologist, James Hutton), was particularly characterised by the creation of clubs. These included the Rankenian Club, the Literary Society of Glasgow, the Aberdeen Philosophical Society, the Oyster Club, the Philosophical Society of Edinburgh (to become the Royal Society of Edinburgh as noted above), the Wise Club of Aberdeen, and the Poker Club. The culture of the Scottish enlightenment was captured by its historian, Alexander Broadie, when he wrote, "thinking was regarded as essentially a social activity. People thought with each other, that is, they *shared* their thoughts" (Broadie quoted in Paganelli 2015: 3; italics in the original).

By 1828, an observer could therefore note of Britain that "in every town, nay almost every village, there are learned persons running to and fro with electrical machines, galvanic troughs, retorts, crucibles, and geologist hammers" (Inkster 1991: 73). By the middle of the nineteenth century, indeed, no fewer than 1,020 institutions of technical and scientific knowledge existed in Britain, with a membership of about 200,000 (Inkster 1991: 78–79). James Dowey (2017) concluded in his survey of those institutions that they comprised "the world's first infrastructure for commercial R&D," which thus facilitated "the acceleration in technological innovation that lay behind the transition to modern economic growth." And on studying the origins of 117 major innovations between 1700 and 1850, Dudley (2012) showed they emerged out of the social networks of which those organisations were the nodes. Those organisations, in short, were the incubators of the Industrial Revolution.

Not all those institutions prioritised research; many were mechanics' institutes, which concentrated on tuition, but those were just as important to technical progress because many of the advances of the Industrial Revolution were micro-advances made by artisans. On 19 October 1826 (p. 459), Dr. Olinthus Gregory told the Deptford Mechanics' Institution that Britain's advances in "agriculture, manufactures, commerce, navigation, the arts and sciences" could be attributed to "[n]ew societies for improvement (among which such societies as this must necessarily be classed)."

Gregory, who taught mathematics at the Royal Military Academy at Woolwich, further praised the Mathematical Society in Spitalfields (founded in 1717) and the Literary and Philosophical Societies of Newcastle upon Tyne, Manchester, Liverpool, Norwich, Sheffield and other industrial and commercial cities, for their promotion of research. Smaller towns were not excepted from these developments, and in the North East, to consider one region, "There were equivalent 'Lit & Phils' at North Shields and Seaham and at Sunderland" (Jackson 2019: 78). These societies, moreover, did not necessarily exclude women: in 1820 the Literary Society of Alnwick (population approximately 5,000) invited Annabel Carr of Newcastle-upon-Tyne, the author of the 1807 book *Conversations on Chemistry*, to lecture on 'mechanics and hydrostatics' (Jackson 2019: 71).

Such societies were particularly associated with eighteenth- and nineteenth-century Britain, not because other countries did not have them – other countries did have them – but because, as Ian Inkster (1991: 78–79) has shown, the British had more than anyone else. We can thus model the take-off of the Industrial Revolution not only as a qualitative matter but as a quantitative one: British industrial research had, in aggregate, crossed the threshold required by the contribution good model.

Meyer (2015) has further shown how the airplane – perhaps the twentieth century's iconic advance – was a product of collective invention. In Meyer's words, "contributors routinely shared inventions and discoveries without explicit exchanges or payoffs … the invention of the first airplanes – a macro-invention – was based largely on open-source information and networks of colleagues." Before the Wright brothers flew in 1903, there were already nearly 50 aeronautical societies and clubs in existence across the globe (mainly in France, Germany, the USA and Britain) sharing information through meetings, newsletter and publications; and Brockett had listed more than 13,000 relevant research publications, and many hundreds of patents, that had appeared by the time he published his *Bibliography of Aeronautics* in 1910 (Meyer 2015).

Meyer has also chronicled how Octave Chanute played the role of information networker amongst the early airplane pioneers, and amongst his many correspondents were the Wright brothers, who sent him no fewer than 177 letters and to whom, in turn, he sent at least 230 letters (Short 2011). The emergence of a person like Chanute is characteristic of the contribution good, for Kealey and Ricketts (2014) have shown that while a public good model of research presents a 'prisoner's dilemma' problem, a contribution good model presents a 'pure coordination' problem, requiring leadership to help resolve it, and the history of the Scientific and Industrial Revolutions (aka the Research Revolution) confirms the importance of such leadership. Thus, coinciding with the advent of those revolutions, a new vocation appeared, that of 'intelligencer.'

One of the first intelligencers was Samuel Hartlib (1600–1662) who, though originally German, settled in London to dedicate himself to receiving and sending letters to fellow researchers, and who by 1630 had forged a network of around 400 correspondents, from all over Europe. Other early intelligencers included Nicolas-Claude de Peiresc (1580–1637), Marin Mersenne (1588–1648) and Ismaël Boulliau (1605–1694), all of whom lived in France, yet the most consequential was to be Henry Oldenberg, the Royal Society's first Secretary and eventual founding editor of the first scientific journal, *Philosophical Transactions*, whose surviving correspondence for the years 1641–1677 exceeds

3,100 letters from all over Europe.[12,13] Other scientific leaders were to include Mary Herbert of Wilton House, Robert Boyle of the Royal Society and Erasmus Darwin of the Lunar Society.

Industrial research was to demonstrate the same phenomenon. So, the Clockmakers Company presented an example of collective leadership, while Joel Lean (*Lean's Engine Reporter*) performed that role for the Cornish mining industry, and as noted above, Alexander Holley performed that role within the Bessemer Association or patent pool, while Arthur Young and Gerard Muntz performed that role within agriculture and steel, respectively. Meyer (2015) has noted, moreover, that the Homebrew Computer Club, from which Apple and many other Silicon Valley start-ups spun out during the 1970s (which, like the free software movement, speaks to the continued vigour of collective invention today) was facilitated by Lee Felsenstein as a latter-day intelligencer; and Meyer (2003) has further noted that such latter-day information networkers are characteristically "charismatic founders who encouraged openness and did not seize chances to keep the technology secret and extract maximum profit."

Eventually, though, profit will be sought. Meyer (2015) and John Scott and Troy Scott (2017) have noted that researchers' incentives shift during the development of a new field of technology: during the early or 'open technology' phase of development, when 'technological uncertainty' dominates, researchers are motivated primarily by psychic reward, and in Meyer's words, "contributors routinely share(d) inventions and discoveries openly without explicit exchanges or payoff." Or, as the Australian aeronautical pioneer Lawrence Hargrave wrote in 1893 of early airplane research, "workers must root out the idea [that] by keeping the results of their labours to themselves, a fortune will be assured to them" (quoted in Meyer 2012). But when data approach close to commercial exploitation, researchers will default

12 John Chamberlain (1553–1628) anticipated the scientific intelligencers by being a political, diplomatic and social intelligencer who met with a wide range of similar intelligencers every day at St Paul's Cathedral between the hours of 11.00 a.m. and 12.00 a.m., and 3.00 p.m. and 6.00 p.m., before writing to his political, diplomatic and domestic contacts with the latest news (Osborne 1689: 449–451). Chamberlain was a good friend of William Gilbert, England's first great scientist, with whom he sometimes lodged, thus showing how Gilbert's style of research, being based on a network of scientific contacts, emerged out of, and overlapped with, similar political, diplomatic and social networks (Thomson 1966: x).

13 The need for scientific intelligencers is perhaps illustrated by Georg Hartmann's discovery of the inclination of the compass, which in 1543 he demonstrated to Charles V and which in 1544 he described in a letter to Duke Albrecht of Prussia. But because the Emperor did not disseminate the information, and because the Duke did not forward the letter to anyone, and because Hartmann apparently did not write to anyone else about the observation (perhaps because he was discouraged by failure of either the Emperor or the Duke to be interested in an observation they all found puzzling), it was lost until inclination was independently rediscovered by Robert Norman, a London instrument maker, who published it in his *Newe Attractive* of 1581. In his pioneering 1269 *Epistola de magnete* or *Letter on the Magnet* (where, like Hartmann and Norman after him, he advocated the experimental method of science), Petrus Peregrinus was luckier than Hartmann, for 39 manuscript copies survive.

in the process Meyer called 'entrepreneurial exit,' to commercialise their discovery: thus the Wright brothers, who were long extremely open in their research, suddenly became secretive in 1903 when they realised they had developed an airplane that worked (Short 2011).

That caesura between pre-competitive and competitive research still operates today. The *Financial Times* described recently how research into Alzheimer's Disease is still at the pre-competitive stage, so the different drug companies have congregated in research roundtables to share their findings. The *Financial Times* reported (cited in Green 2019) of Dr. Mintun, a vice president for R&D at Eli Lilly:

> Lilly's Dr Mintun is encouraged: "It is hard to find an example of such a major disease in which pharmaceutical companies and academic scientists collaborate more than we do in Alzheimer's."
>
> Research roundtables, such as those organised by the Alzheimer's Association, have created "places where we can talk in a pre-competitive way and ask: 'Are there are ideas that haven't had enough hearing? Are there new diagnostic techniques that could affect the way we do trials?'"
>
> Disappointing trials involving BACE inhibitors,[14] which impeded the enzymes that led to the creation of amyloid, started to fit together once companies shared their findings.
>
> "Companies had clinical data that individually they might struggle to make sense of, but when they shared this, we could quickly understand what it meant and make sure we rapidly gained understanding." He challenges the popular narrative that pits large pharma companies against each other in a race to discover a blockbuster cure. "This is genuinely an area where, if any company announced good results, we would all be happy," he says.

Academic scientists, too, will exit when their data come close to publication. Doudna and Sternberg (2017: 242) wrote in their account of the discovery of CRISPR that the "twin poles of science [are] competition and collaboration," which Philip Marsden (2020: 35) echoed when he wrote of the "camaraderie and competitiveness" of research, and which is how the model of innovation as a contribution good remains economically benign, because contribution goods continue, even amongst commercial competitors, to promote the sharing of knowledge: thus Mansfield (1985) has shown that, thanks in part to the mutual contribution of knowledge, industrial secrecy is a myth, and competitors know of each other's advances within 12–18 months of their having made them. Thus we also see that the contribution good is, amongst other things, a mechanism for dispersing second-mover advantage across the research and therefore the industrial communities. James Schmitz (1989) has modelled second-mover advantage as the basis of both

[14] β-site amyloid precursor protein cleaving enzyme inhibitors.

https://doi.org/10.1017/9781108692915.003 Published online by Cambridge University Press

economic growth and of private profit, and the operation of the contribution good is compatible with that model.

To conclude this section, it can be seen that ever since Allen wrote his 1983 paper on collective invention in the Cleveland steel industry during the nineteenth century, further examples have multiplied, and it is probable that many more examples will emerge once the conventions in the discipline change: some economic historians see industries as being either patent-driven or collectively driven (so they look for collective invention only if an industry seems not to be patent-driven) but this may be a false dichotomy, because in the process of entrepreneurial exit many industries may foster patents against a background of collective invention. Thus, Meyer (2015) describes how researchers "may optimally work together, even anticipating that one of them will want to break away when he or she suddenly sees an outside option to (perhaps) get rich."

That an industry is characterised by patents, therefore, does not preclude the possibility that collective invention nonetheless underpins the growth of that industry.

1.7 INTERNATIONAL COMPARISONS

Recognising research as emerging out of institutions of mutual contribution highlights an intriguing historical lacuna. We've already noted two proto-industrial revolutions in Italy and the Netherlands respectively, and each was associated with the inauguration of collective institutions of knowledge exchange; the Western world's first university, Bologna, was founded in 1088, while the Dutch agricultural revolution, which emerged from a cooperative or 'polder' culture, was associated with the creation of universities such as the University of Leuven (1425; Vesalius and Mercator were graduates). Yet, though it has long been recognised that Chinese science and technology were, in many respects, long in advance of Europe's, China nonetheless had no Industrial Revolution. And China appears never to have created associations for the pursuit of knowledge. Universities, for example, represent such associations, but as Macfarlane (2002) wrote: "Another kind of association, for the pursuit of knowledge, is the university, an archetype in the west of fellowship and equality . . . yet it never developed in China and Japan."

The university is only one type of institution that nurtures the contribution good, but the absence of universities in China reflects the fact that China seems not to have produced societies such as the Royal Society or the Lunar Society for the mutual advance of science and technology. Its advances were therefore limited only to those of individuals, which under a model of the contribution good would preclude the development of an Industrial Revolution.[15]

[15] Kelly argues that China's markets were sufficient to maintain only Smithian as opposed to Schumpeterian growth (Morgan Kelly 1997: 939–964). Needham argued that China failed to

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It was Japan that was to realise "the first completely successful instance of Asian assimilation of modern Western manufacturing technology," which Japan achieved during the nineteenth century in cotton-spinning Saxonhouse (1974: 150). And Saxonhouse showed this was achieved by the different firms, though being highly competitive, nonetheless sharing knowledge with each other with marked openness in the Dai Nihon Bōseki Rengōkai (All Japan Cotton Spinners Association).

Saxonhouse also showed that the Japanese success in cotton-spinning occurred only after the government had ceased to involve itself in the industry, which illustrates a recurring theme; thus, Lux and Cook (1998) have advanced an observation that further illustrates British *laissez faire* advantage during the seventeenth century over France's research under absolutism and *dirigisme*. Complementing its role as a collective research laboratory, the Royal Society also operated as a node in a long-distance information network; when, for example, in July 1665 Henry Oldenburg, the Secretary of the Royal Society, received a letter from a researcher in Lyons, France, describing a novel spherical mirror; he wrote to at least ten other researchers (probably more, but not all the correspondence has survived) with the news. And he received at least 11 letters of commentary (five from abroad) in response.

But Oldenburg's information network was disrupted after 1666 when the French King created the *Academie des Sciences*. The *Academie* crowded out the pre-existing, private, Thevenot Academy in Paris, but whereas Thevenot Academy had promoted the open disclosure of knowledge, the *Academie* opened under an official policy of secrecy. Whereupon Oldenburg's most important French correspondents simply stopped corresponding usefully. So in December 1666 Adrien Auzout, who had been writing to Oldenberg on a monthly basis, wrote to apologise for his silence over the previous six months with: "Although I had the honour to be appointed by the King as a mathematician and physicist, I can't give you more details than are known to everybody," while by December 1667 Henri Justel, another of Oldenburg's most assiduous correspondents but not an academician, is writing, "I cannot tell you what our academicians are to work at, as they keep it secret." In the words of Lux and Cook, the founding of "the Paris Academy and the closing of the Thevenot seriously broke the chain of communications." Only with the reforms of 1699, a third of a century later, did the *Academie* embrace openness; thus had the government funding of science in France held back the advance of knowledge.

Further, the *Academie* excluded entrepreneurs. So Francis Vernon, the secretary to the English ambassador, reported in May 1669 that: "[T]he Royal Academie are not as ours in Engld – a great assembly of Gentlemen, Butt only a few Persons wch are eminent [in science], & not in number above 13. or 14." No-one was recognised

create a Scientific or Industrial Revolution because it failed to generate "a mercantile culture" (Joseph Needham 2003: xiii). Here we need note only the absence in China of associations for the pursuit of knowledge.

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by the *Academie* unless he was already an academician in receipt of a state salary of 1500 Livres per annum, whereas – in contradistinction – the Charter of the Royal Society conferred upon it the freedom "to enjoy mutual intelligence and knowledge with all and all manner of strangers and foreigners, whether private or collegiate, corporate or politic, without any molestation, interruption, or disturbance whatsoever."

The Royal Society's Charter thus incarnated a similar culture to that of the Greek city states of the first Scientific Revolution, as was articulated by Pericles in his funeral oration of circa 430 BCE, as quoted by Thucydides in his *History of the Peloponnesian War*: "We throw open our city to the world, and never by alien acts exclude foreigners from any opportunity of learning or observing" (Thucydides 2000). Thus the linkage that private societies such as the Royal Society achieved in England, when they brought together holders of financial capital and creators of human capital, and which the private Thevenot Academy had fostered, was destroyed in France when the state started to fund science. And governments can still seek to supress the free creation and sharing of knowledge. As revealed by the title of his book *Crypto: How the Code Rebels Beat the Government – Saving Privacy in the Digital Age* (2001), Steven Levy reported how the US and UK governments sought to suppress not only their own research into public-key technologies but also that of private sector businesses. The federal government in the USA, moreover, has systematically obstructed research into psychoactive agents (Burrus 2019) despite their therapeutic potential (Carhart-Harris et al. 2016).

Vernon's report of how the Royal Society attracted to its meetings "a great assembly of Gentlemen" further supports the suggestion that academic science and commercial research advanced together from the seventeenth century. Thus Francis Bacon, during his years as a senior law officer, 1607–1621, handled about 20 of the 40 patents Parliament then awarded (patents were then awarded by Act of Parliament) and he personally oversaw patents for the "making of copper by dissolution," "water pumps," "tillage of seeds," "conversion of iron into steel," "making of salt," and the "making of glass by sea coal and pit coal." His patentees included Sir David Murray, Lord Edmund Sheffield, Sir John Bourchier, Lord Philip Herbert, Sir Thomas Howard, Sir Robert Mansell, Sir Edward Zouch and Lord Edward Somerset (Pastorino 2017), which illustrates how the social and financial elite in England was then committed to innovation – which was why its members were to attend the meetings of the Royal Society, and which was how the French were to damage themselves when, on their government funding science, they excluded the private sector from the meetings of the *Academie*.

That markets fostered innovation better than did governments was well-understood by British Industrial Revolutionaries. Friedrich Koenig was the German inventor of the high-speed steam-powered printing press, which inaugurated mass-circulation newspapers (*The Times* converted to Koenig presses on 29 November 1814), and Koenig spoke of:

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> *The well-known fact* that almost every invention seeks, as it were, refuge in England, and is there brought to perfection, seems to indicate that the continent has yet to learn from her the best manner of encouraging the mechanical arts. I had my full share in the ordinary disappointments of continental projectors, and after having spent, in Germany and Russia, upwards of two years in fruitless applications, I proceeded to England. [italics in the original]
>
> (Gregory 1826: 459–460)

Or, in Dr. Olinthus Gregory's words to the Deptford Mechanics' Institution (1826: 460): "What could not be accomplished by the encouragement of *princes* on the continent, was effected by the aid of private individuals in London" [italics in the original].

1.8 CONCLUSION

We do not suggest that commercially motivated research is the only agent of growth in a modern economy: since the sixteenth century there have been philanthropic, geopolitical and swagger research, which might have stimulated growth. There may be, moreover, some marginal uncompensated spillovers of knowledge, which are emphasised by standard analysis of the economics of science and which are used to make a case for greater levels of research effort. And there will always be secret research, which will produce sub-optimal levels of aggregate growth. The research landscape is therefore complex, yet we nonetheless suggest that the contribution good model of scientific knowledge best explains modern rates of economic growth. In particular, the explosive rate of growth it generates once a threshold has been passed will also account for the explosion of economic growth from circa 0.04 per cent PA to circa 1.8–2.0 per cent PA that characterises the lead industrialised countries today.

The spontaneous 'take-off' that occurs when a sufficient 'critical mass' of scientists and entrepreneurs has been achieved clearly implies that McCloskey's 'bourgeois virtues' have evolved and taken over from aristocratic norms. Without the 'bourgeois deal' and the attraction of talented people to the pursuit of commercial gain, the system would lose its motive force. Our point, however, is that recognising the nature of knowledge as a 'contribution good' rather than a 'public good' is crucial to explaining the historical record. If scientific knowledge is a pure 'public good,' then bourgeois values in themselves will not produce an industrial revolution. Indeed it is possible to argue that the evolution of the 'bourgeois deal' itself would have been much more difficult if scientific advance had, in the nature of things, to be derived from courtly, centralised and elite efforts to raise productivity rather than being the outcome of decentralised commercial activity and the pursuit of 'trade tested betterment' to use McCloskey's phrase.

https://doi.org/10.1017/9781108692915.003 Published online by Cambridge University Press

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