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#2014-082

The Republic of Open Science: The institution's historical origins and prospects for continued vitality

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UNU-MERIT Working Papers

ISSN 1871-9872

Maastricht Economic and social Research Institute on Innovation and Technology, UNU-MERIT

Maastricht Graduate School of Governance MGSoG

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The Republic of Open Science
The institution's historical origins and prospects for continued vitality

By

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June 15, 2014

To be published by the Accademia Nazionale dei Lincei (Rome, Italy) in
Contributi del Centro Linceo Interdisciplinare 'Beniamino Segre', Fall, 2014

Abstract

In most modern economies scientific and technological research activities are conducted in two distinct organizational modes: commercially oriented R&D based upon proprietary information, and non-commercial "open science." When taken together and kept in proper balance, these form a *complementary* pair of institutionally differentiated sub-systems. Each can work to amplify and augment the productivity of the other, thereby spurring long-term economic growth and improvements of social welfare in knowledge-driven societies. This paper considers the difference between historical origins of open science and its modern, critically important role in the allocation of research resources. The institutional structure of 'The Republic of Open Science' generally is less well understood and has less robust self-sustaining foundations than the familiar non-cooperative market mechanisms associated with proprietary R&D. Although they are better suited for the conduct of exploratory science, they also remain more vulnerable to damages from collateral effects of shifts in government policies, particularly those that impact their fiscal support and regulatory environments. After reviewing the several challenges that such policy actions during the 20th century's closing decades had posed for continued effective collective explorations at the frontiers of scientific knowledge, the discussion examines the responses that those developments elicited from academic research communities. Those reactions to the threatened curtailment of timely access to data and technical information about new research methods and findings took the form of technical and organizational innovations designed to expand and enhance infrastructural protections for sustained open access in scientific and scholarly communications. They were practical, "bottom-up" initiatives to provide concrete, domain relevant tools and organizational routines whose adoption subsequently could be, and in the event were reinforced by "top-down" policy guidelines and regulatory steps by public funding agencies and international bodies. The non-politicized nature of that process, as well as its largely effective outcomes should be read (cautiously) as positive portents of the future vitality of the Republic of Open Science – and of those societies that recognize, protect and adequately support this remarkable social innovation.

Keywords: science and technology policy, open science, new economics of science, evolution of institutions, patronage, asymmetric information, principal-agent problems, common agency contracting, social networks, 'invisible colleges,' scientific academies, intellectual property rights, anti-commons, contractual construction of commons

JEL Codes: D8, H4, O3

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By

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Prologue

Programs of exploratory research in science and engineering that are conducted in accord with "open science" principles are widely acknowledged to be critical for sustaining long-term economic growth and welfare improvements. Yet, the culture and practices of open science also remain particularly exposed and vulnerable to the unintended consequences of disturbances in larger, inter-twinned technical, institutional, economic and political systems in which it is embedded, and upon which it depends. This vulnerability became apparent in the course of the past three decades, during which a sustained movement strengthened national and international intellectual property rights protections and the scope of those legal regimes to encompass much of the now pervasive digital information environment.[1] Restrictions on timely access to scientific data, information and research tools that the owners of legal monopoly rights in patents, copyrights, and database rights were able to impose had the effect of exacerbating problematic effects of other policies affecting universities and publicly funded research

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* Like my invited lecture to the *Centro Linceo Interdisciplinare* Conference on 23rd April 2013, the second and third sections of this paper draw heavily upon material in a much longer previous essay, David (2008). One will find there fulsome acknowledgement of my intellectual debts to many friends and colleagues who assisted my historical research on the origins of open science. Sheila Ryan Johansson's careful reading of the penultimate draft, and her gift for untangling and shortening my sentences, greatly improved the exposition in this version. I am grateful too for the contributions made by Mario Pianta to the organization of the Conference, which provided stimulating commentaries from the other participants, and for his patient assistance in my preparation of the present text for publication.

[1] For entry points to the issues surrounding intellectual property rights and university-industry R&D collaborations, and references to the vast literature on the consequences of the Bayh-Dole and Stevenson-Wydler Acts in the U.S., see e.g., Smith (1990), David, Mowery and Steinmueller (1994), Mowery et al. (2004: ch.5), David (2004, 2005, 2007a), David and Hall (2006); Guston and Keniston (1994) on university relations with the federal government; Branscomb (1994), Cohen and Noll (1994) on "privatizing" the National Labs. For the role of the public domain in scientific and technical data and information, see David (2003) and other contributions to the same National Academy of Science Symposium publication.

institutes. In a widening circle of countries a variety of attempts were made to emulate particular features and sequelae of the U.S. Bayh-Dole Act of 1980 -- without grasping the conjuncture of special circumstances and purposes that had given rise to that piece of congressional legislation. This resulted in the transfer to their universities and institutes the locus of control of patenting and managing the commercial exploitation those and other intellectual property rights derived from publicly funded academic research findings. University "technology transfer offices" were thus promoted as agencies through which the benefits of such public expenditures could be "valorized" in monetary terms, either by licensing the patented inventions for further development and eventual use in production by existing business firms, or by assigning them to new "start-up" companies in exchange for possible future claims on equity in those enterprises.

The new incentives that were created, along with the legitimating "public policy" rationale of "transferring technologies" for growth-stimulating private investments in innovation, tended to further encourage academic researchers' in delaying and denying "outsiders" access to raw data-streams, technical procedures, transfers of research materials (e.g., cell lines and microbial cultures), as well as memoranda on the findings of completed but unpublished research results from their ongoing projects. In doing so, the new regime initiated by the Bayh-Dole Act and the ensuing mimetic internationalization of "academic entrepreneurship" had the unintended perverse effect of augmenting a pre-existing chronic source of drag on the pace of collective scientific advances of the research frontier: it further inhibited the rapid verification of new research findings, or their swift qualifications and correction by expert research peers, thereby impeding the further extension of research based on the latest theoretical and empirical advances.[2]

The conditions just described perversely worked to degrade the effectiveness of the scientific research system as a whole, inasmuch as their deleterious effects were not confined to exploratory academic investigations. Considered at the macro-level, the two modes in which scientific and technical research activities are organized in modern economies --"open science" and commercially oriented R&D based upon proprietary information -- together form a *complementary* pair of institutionally distinct sub-systems. The public policy challenge that needs to be faced for the long-run, consequently, is to keep the two sub-systems in proper productive balance, so that the special capabilities of each

[2] The concluding section's discussion provides a fuller account of these and other largely unanticipated and dysfunctional ramifications of the Bayh-Dole Act that became increasing visible during the 1980's, the reactions that they eventually elicited from influential sections of the U.S. academic research community.

may amplify the productivity of the other. Additions to the body of reliable scientific knowledge renew and enhance the private and societal payoff from applications oriented R&D seeking commercially profitable innovations.[3]

Yet, the former of these sub-systems, being grounded in career incentives and norms of scientific behavior that restrain opportunism and foster cooperative behaviors on the part of researchers whose work is dependent on public and private patronage for support, remains the more fragile of the pair. Without adequate material support and reinforcement of its norms by the policies and procedures of its primary funding agencies, the practice of "open science" and its institutional infrastructure are vulnerable to being undermined by restricted sharing of "research process knowledge" and other (non-cooperative) behaviors motivated by the goal of privately appropriating economic "rents" from monopolistic possession of new scientific and technical information.

This implies that the "balancing act" for public policy requires more than maintenance of public funding for exploratory research projects carried on in universities and public institutes. It may call for deliberate measures to halt, and in some areas even reverse excessive incursions of claims to private property rights over material that would otherwise remain in the public domain of scientific data and information – in other words, for the protection of an "open science domain" from the regime of legal protections for intellectual property rights, and the individual competitive impulse to impede access to those vital research resources by potential rivals.[4] Nevertheless, not very long ago many writers in the business press, academic economists, lawyers, and government policy-makers saw this matter very differently – and some still do so today.

The centrality of information technologies and information goods in the phenomena that were associated with the "New Economy" euphoria and its disruptive

[3] On this and related challenges for integrating practical, mutually self-reinforcing economic policy measures affecting science, technology, innovation, long-run economic growth, see e.g., Aghion, David and Foray (2008).

[4] The case for this position is argued in David (2000, 2004, 2005) not only in regard to patenting, but also concerning the potential effects on exploratory scientific research in many scientific domains that may result from exploitation of the legal protections of databases created by the EU Database Directive of 1998. On analytical and empirical questions concerning the seriousness of the so-called "anti-commons" arising from patenting of research tools in biomedical sciences, see, e.g., Walsh, Arora and Cohen (2003); and David (2003, 2011) for somewhat divergent perspectives. Understandably, much of the science policy literature continues to focus upon issues of funding, but there are legal and other institutional impediments to academic research collaborations – and not only those relating to IPR. David (2006 b) and David and Spence (2003: esp. pp. 45-53; and 2008) examine these obstacles in the context of the hopes for a new age of global collaboration brought about by e-Science and Grid computing infrastructures, and propose a variety of ameliorative institutional innovations.

institutional sequelae at the turn of the Millennium suggested that the world had left behind the epoch of material capitalism; that we had moved into on a new and different stage – that of "Intellectual Capitalism", which it should be the purpose of public policies to perfect, as it has sought to perfect the workings of markets for ordinary commodities. Accordingly, on this new view, the way forward called for assuring the continued vitality of the market system in the domain of information and data. Moreover, it was seen that for that tasks, new technical and institutional tools were available: digital information technologies and computer- mediated telecommunications networks, which in combination with novel statutes and judicial interpretations affecting legal protections of intellectual property rights would provide reliable private control over the management at exploitation of "knowledge assets." This, however, was something of a two-edged sword. While it tended to reinforce the defenses of incumbent firms in existing markets that were drawing "rents from their holdings of patents and copyrights, it also expanded the opportunities for the entry of new rivals – unexpectedly armed with market-disrupting technological innovations.

Too much responsibility for the shifted balance of science and technology policy -- from state patronage and towards reliance on property rights monopolies, should not however be laid at the door of the digital information revolution. The broader, and increasingly perceptible swing of the policy pendulum in the U.S., and several of the leading economically and scientifically advanced EU member states, received impetus and gained momentum from the contemporaneous intensification of global economic competition, as well as from the straightened fiscal conditions under which the governments of those nations were operating throughout much of the decade preceding 1989. The latter developments had emerged not from any coherent set of policy decisions, but rather from a diverse multiplicity of *ad hoc* reactions to events, incremental alterations of public sector budget priorities, realignments of government agency and institutional missions, as well as legislative and judicial extensions of the scope of legal protections afforded to owners of intellectual property rights.[5]

[5] Competition among leaders and followers in international markets for high-tech manufactures, combined with the post-Cold War ascendance of "free market ideology" eventually to focus U.S. and other western nations on pursuing international strategies of opening foreign markets by trade liberalization agreements while tightening IPR protections for "innovative" products – of which the 1994 TRIPS Agreements under the newly formed World Trade Organization was emblematic. For further discussion of U.S. international policy on IP protection from the 1970s onwards, see David (2000), Ullrich (2005); on the impacts of IPR protections under TRIPS , see Archibugi and Filippetti (2010); Henry and Stiglitz (2010).

In this vision of the brighter future, the dark threat that needed to be contained is the one arising from the free and open circulation of ideas, data and information. "Tacit-ness" then could be embraced as a welcome aspect of cognitive behavior, restraining and localizing the relentless transformation of implicit and unexpressed human knowledge into explicit codified information, which permits its virtually costless reproduction, communication and those ubiquitous "spill-overs" that interfere with the complete private appropriation of wealth and power from science.[6]

For readers with the range of present-day concerns that have just been reviewed, the thrust of this essay's contribution to the social and economic history of modern science is simply stated: pursuing the policy path toward the envisaged perfecting of "Intellectual Capitalism" as an integrated technologically implemented market for privately owned bits of information and data would lead the global enterprise of scientific research, and all that depends upon its sustained vigor towards the truly darker past from which western European societies quite fortuitously managed to escape in the seventeenth century.

The modus of that liberation – one could say the dawning of an "enlightened" collective pursuit of scientific knowledge" -- was provided by the inter-twinning of intellectual and institutional transformations that first coupled the Scientific Revolution of that era with the growing adherence to new attitudes and practices regarding the disclosure of "Nature's Secrets." This emergent ethos subsequently reinforced the institutionalization and stabilization of public patronage of researchers in the "Republic of Science."[7] It then gave rise to a new, institutionalized system of fruitful interactions with proprietary, market-oriented R&D activities that were also moving away from

[6] See Cowan, David and Foray (2000) for a critique of this strain that appeared in writings on "tacitness", "sticky data" and science and technology policy during the latter half of the 1990's, and a quite different conceptual framework for treating the subject.

[7] Modern use of the phrase "Republic of Science" by Michael Polanyi (1962) transparently evoked the broader humanist metaphor of a self-governing, trans-national intellectual polity whose transactions conducted by civil discourse in the universal language: the *respublica literari*. The "self-governing" nature of (open) scientific communities was first examined by Polanyi (1942), contemporaneously with Merton's (1942) essay on the normative structure of science. On roots of the 18th century Enlightenment in the Renaissance "Republic Letters", see e.g., On the further incipient conceptual link with open scholarly communications in the 17th century, see MacLean's (2008) inquiry into the nature of the "Republic of Medical Letters" in century preceding the Thirty Years War, based upon correspondence that was preserved by the post-1520 flourishing of the genre of printed collections of "letters" composed by representatives of the new breed of university-trained physicians --many of whom figured in the ranks of the leading European scientists of that epoch.

predominant reliance upon secrecy, towards greater use of legal protections afforded by (open) patents.[8]

To closely read the complex story of the transformations that created the ethos of open science and the subsequent institutionalization of its practices is a useful step towards fuller appreciation of the degree to which the constellation of differentiated institutions supporting and shaping the conduct of scientific and technical research is in reality a quite fragile cultural construct. As I shall try to indicate within the brief compass of this paper, we are dealing with the legacy of an extended, intricate and contingent historical process that cannot be assumed to have been produced by some underlying self-balancing, and auto-regenerative system – one that that has arisen purely in response to the imperatives of modern scientific technique and therefore requires neither social maintenance nor political protections.

True, as is the case with many social structures, the institutional infrastructures of ''open science'' can be seen to possess a measure of plasticity. But elasticity has limits. Consequently, along with other delicate pieces of (social) machinery, a substantial measure of caution and patience in seeking to first thoroughly understand the manner of its construction and its present workings would seem the minimum that should be asked of those having the power to tinker with this important institutional component of infrastructure for the modern system of innovation. That much precaution seems called for, especially where reformers are moved to experiment and "innovate" in order to find a "quick fix" for one or another among the myriad (often rather transient) societal problems that have brought themselves to the notice of people in elected offices.

Examining the strands of internal intellectual development fused into "mechanical philosophy", and the nexus of "external" economic, social and political forces that shaped the early practices of open science and its connections with the Scientific Revolution of the seventeenth century, leads one to appreciate the emergence of this complex of institutionalized behaviors in western Europe as an extraordinary piece of cultural good fortune. Perhaps that perception will serve to heighten awareness of the potentialities of unintended and unwanted consequences that are latent in efforts to hastily re-orient complex and venerable social institutions in order make them serve new purposes that are

[8] On the historical origins of patent rights and the patent system's early institutional evolution, see Hill (1924), David (1993, 1994) and references therein.

far different from those for which the course of their historical evolution has left them well adapted.

Such an inquiry, in effect, asks contemporary economists and economic historians to turn away from their preoccupations with probing resource allocation mechanisms in the interior of the "black box of technology" – for at least long enough to develop a clearer view of what goes on inside the other major component of modern research and innovations systems, the still comparatively unexamined "black box of science." Although the open science system has begun to be systematically explored during the past two decades using the tools of economic analysis,[9] far more remains known and understood about the intellectual property protection mechanisms that enable private appropriation of research benefits, and the evolving institutional structures affecting proprietary R&D resource allocation.

The desirability of closing that particular lacuna in the economics and economic history literatures has been as evident to those who have perceived it within a broader concern with the economics of institutions, and also to philosophers, sociologists and historians who have approached from the perspectives of science and technology studies. Consequently, a growing company of economic and technological historians, along with economists of an historical persuasion, have begun to turn their attention to studying the scientific foundations of the modern "knowledge economy."[10] Nevertheless, this rapidly growing literature continues to be preoccupied (understandably enough) with pressing contemporary questions about the performance of these institutions and the people who work within them. It rarely pauses to ask how the modern world came to have two quite different and in some respects antithetical modes of organizing and allocating resources for the pursuit of reliable knowledge. The answer proposed in these pages is, then, a

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[9] On the "new economics of science" program to redress this comparative neglect through research in the microeconomics of resource allocation within publicly supported science, see Dasgupta and David (1987, 1994), David (1994b, 1998, 2002 2003), David, Mowery, Steinmueller (1992), and surveys by Diamond (1996), Stephan (1996), and David, Foray and Steinmueller (1999), den Besten, David and Schroeder (2010). Note should be taken of the harvest of interesting and ingenious quantitative studies emerging from a younger generation of economists, including Arora, David and Gambardella (1998), Geuna (1999), Carayol (2003, 2007), Carayol and Dalle (2000, 2007). On the problematic aspects of the interactions between the regime of intellectual property rights protections and academic science, see also the quantitative studies by Walsh, Arora and Cohen (2003), Murray (2006, 2010), Murray and Stern (2007), Gans, Murray and Stern (2010), Williams (2012).

[10] In addition to the works cited below as specifically germane to the institutional history on which this paper focuses, see the variety of topics addressed, e.g. by Lécuyer (1998), Lenoir (1998), and the broader, less institutionally specific treatments available to be found in Headrick (2000), Mokyr (2002:Ch.2; 2009:Chs.2-3), and Foray (2004).

contribution to the economic history of modern science that may be read as offering insights from the past that carry implications for the present and the future.

The puzzling historical emergence of "open science"

An essential, defining feature of modern science thus is found in its public, collective character, and its associated ethos of cooperative inquiry and free sharing of research findings that were famously articulated by Robert K. Merton.[11] The institutional features of prime interest here are those that most sharply distinguish the sphere of "open science" (supported by public funding and the patronage of private foundations) from both the organized conduct of scientific research under commercially-oriented proprietary rules regarding data and information, and the production and procurement of defense-related scientific and engineering knowledge under conditions of tightly restricted access to information concerning R&D results having actual or potential applications.

While to most of us the idea of science as the pursuit of "public knowledge" seems a natural, indeed a primitive conceptualization, actually it is a social contrivance. Moreover, its expression and institutionalization in the practice of open science is a comparatively recent innovation, one that began to take recognizable form in European toward the close of the sixteenth century and emerged clearly during the first half of the seventeenth century.[12] This development should be seen as a vital and distinctive aspect of the Scientific Revolution of that era, from which there crystallized a new set of social conventions, incentive structures, and institutional mechanisms that reinforced scientific researchers' commitments to rapid disclosure and wider dissemination of their new discoveries and inventions.

The epistemological transformation effected by the fusion of medieval experimentalism with Renaissance mathematics has been the subject of an enormous

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[11] Merton (1973), Chs. 11, 12 reprinted from Merton (1938/1970), and Ch. 13, reprinted from Merton (1942); also, Merton (1996: Chs. 20-24, Ben-David (1991: esp. Parts IV and VI). See Ziman (1994, p. 177) for the suggested mnemonic device for recalling the principal Mertonian norms: *CUDOS* -- *C*ommunalism, *U*niversalism, *D*is-interestedness, *O*bjectivity, *S*cepticism.

[12] As close to the present as that is, considered in historical time, it dates the emergence of new idea of science as a shared, public endeavour as having occurred well more than a half -century before the establishment in Paris and London during the 1660s of scientific societies as formal institutions under royal patronage. This chronological shift represents the consensus of subsequent historical research (esp. that which, following McClellan (1985), which has done much to correct the misleading impressions conveyed by Ornstein (1928) and Brown (1934) in regard to the instrumental role that these early state-sponsored scientific societies had played in creating the new ethos of science as the cooperative pursuit of shared knowledge. Surprisingly, however, strong echoes of that the latter view still are found in modern surveys of the history of science, e.g., Pyenson and Sheets-Pyenson (1999: Ch. 3 – on "Sharing").

literature that focuses on tracing the intellectual foundations upon which those late sixteenth and early seventeenth century developments rested. Figure 1 reprises the familiar main lines of continuity in a schematic outline of the Scientific Revolution's antecedent intellectual sources.[6] But, the late sixteenth and early seventeenth centuries also witnessed a transition from the previously dominant ethos of secrecy in the pursuit of Nature's Secrets, which gave way to a new set of norms, incentives and organizational structures. These institutional transformations reinforced scientific researchers' commitments to rapid disclosure and wider dissemination of their new discovers and inventions.

(Figure 1 here)

Yet, the puzzle of why and how this came about has not received the notice it would seem to deserve, especially in view of the complementarities and tensions that are recognized to be present today in relations between the regimes of 'open' and 'proprietary' science. Even superficial reference to the antecedent intellectual orientation and social organization of scientific research in the West suggests the utter improbability of the historical bifurcation that this involved. For, it saw emerge alongside and in some sense in competition with the older, secretive search for 'Nature's Secrets,' a new and quite antithetical mode of conducting 'the hunt for knowledge.' Virtually all of the intellectual traditions and material conditions in the medieval West inveighed against 'openness' of inquiry and public disclosure of discoveries about the natural order of the world, let alone the heavens. Medieval experimental science was shaped by a political and religious outlook that encouraged withholding from the "vulgar multitude" arcane knowledge that might bring power over material things. The imperative of secrecy was particularly strong in the medieval and Renaissance traditions of Alchemy, where, indeed, it persisted side-by-side with the emergent institutions of open science throughout the 17th and into the 18th century[13]. Social and economic regulations during the Middle Ages, along with the relatively primitive and costly technologies available for scientific communications, also reinforced the moral and philosophical considerations arrayed against open disclosure of discovered secrets. Economic rent-seeking worked in the same direction: knowledge of

[13] See David (2008: pp. 9-11, 23-24) for discussion of Thorndike (1950:vol. II), Eamon (1985, 1994) on medieval arcane knowledge and experimental science; Vickers (1984) on Renaissance alchemy; and Dobbs (1975), Westfall (1980), Feingold (1984) and Figala and Petzold (1993) and the "chemico-alchemical practices that deeply engaged leading early modern scientists, including Robert Boyle and Isaac Newton.

recently discovered geographical secrets that were held to be of potential mercantile value, such as trade routes, would be kept from the public domain. Similarly, craftsmen normally closely held technological recipes, even when they were not compelled by guild restrictions to preserve the 'mysteries' of the industrial arts.[14]

Why then, out of such a background of secrecy and obfuscation, should there have emerged a quite distinctive community of inquiry into the nature of the physical world, holding different norms regarding disclosure, and being governed by a distinctive reward system based upon priority of discovery? Why so? The question is striking especially in the modern context, where one may see that there is little if any difference between the methods of (scientific) inquiry used by university scientists working under the institutional norms of open science, and the procedures that they (or others with the same academic training) employ in the setting of a corporate R&D laboratory? Can the social organization of open science then be simply an epiphenomenon of the profound philosophical and religious re-orientations that have been presented as underpinning the Scientific Revolution, if not the epistemological transformation that latter had wrought? Or, should the intellectual achievements of that epoch instead be read as consequences of what might be called the "Open Science Revolution”? To state the problem more synthetically, is it not plausible that these two discontinuities – the one taking place in the social organization of scientific inquiry and the other transforming its intellectual organization – were interdependent, and entangled with each other in ways that need to be more thoroughly understood?

A start towards answering this question is provided by considering the economic logic of the organization of knowledge-producing activities, for, it is possible in such terms to give a complete functionalist account of the institutional complex that characterizes modern science. In brief, the norm of 'openness' is 'incentive compatible' with a collegiate reputational reward system based upon accepted claims to priority; and it is conducive to individual strategy choices whose collective congruence reduces excess duplication of research efforts, and enlarges the domain of informational complementarities. This brings socially beneficial ‘spill-overs’ among research programs, and abets rapid replication and swift validation of novel discoveries. The advantages of treating new findings as "public

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[14] On secrecy about maps relating geographical discoveries and new trade routes, and craft-guild “mysteries” and anti-competitive practices restricting the dissemination of technical knowledge, see the discussion in David (2008) based on Thrupp (1942, 1963), Unwin (1964), Long (1991), Hilaire-Pérez (1991, and 2000: esp. pp. 136-142). See also the critique by Ogilvie (2004) of recent efforts to re-cast the early modern European craft-guilds in the role of an efficient pro-innovation agency.

goods" in order to promote the faster growth of the stock of knowledge, thus, are contrasted with the requirements of secrecy for the purposes of securing a monopoly over the use of new information that may be directly or indirectly exploited to produce goods and services, or further knowledge.[15]

The preceding rationale provides important explanatory insights regarding the survival of the constellation of open science norms and institutions in most of the modern, scientifically and technologically advanced economies. It does so by highlighting the functional contrast between those institutional arrangements that are well suited for maximizing the rate of accumulation of knowledge, on one hand, and on the other hand, the social and legal arrangements that support market mechanisms -- which are far better suited for maximizing a society's extraction of economic rents from the existing state, or "stock" of reliable knowledge. This juxtaposition of complementary functions suggests a logical basis for the existence and perpetuation of institutional and cultural separations between two normatively differentiated communities of research practice: the open 'Republic of Science' and the proprietary 'Realm of Technology'. This juxtaposition suggests a logical basis for the existence and perpetuation of institutional and cultural separations between two normatively differentiated communities of research practice, the open 'Republic of Science' and the proprietary 'Realm of Technology': the two distinctive organizational regimes serve not only different, but potentially complementary societal purposes.

Yet, the "logical origins" style of explanation for the co-existing institutions of modern science and technological development entirely abstracts from (which is to say, ignores) the specific social and economic circumstances of their emergence and ensuing historical evolution. Such a rationale would seem to presuppose, at best, a form of 'creationist' fiction – namely that these arrangements were instituted *ab initio* by some external agency, such as an informed and benevolent political authority endowed with fiscal powers. Objections to this particular fiction (on the evidentiary grounds that at the moment of institutional genesis no such agency was present) calls for an explicit inquiry into the 'historical origins' of the institutions of open science, since these remain outside the set of 'logical origins" that one arrives at by simply considering the present-day functional value of an already extant, cooperative mode of scientific research.

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[15] For further exposition, see Dasgupta and David (1987, 1994), David (2003), and David, den Besten and Schroeder (2010).

***Genesis*: Noble patrons, mathematicians, and principal-agent problems**

Rather than accepting an essentially "idealist" approach to the problem, which would construe the reorganization of scientific activities in early modern Europe as having somehow derived automatically from the intellectual changes represented by the new style of 'scientific' activity, I have proposed that the historical emergence of the norms of disclosure and demonstration, and the rise of "cooperative rivalries" in the revelation of new knowledge, had independent and antecedent roots.[16] These are to be found in the social, material and institutional contexts in which the new breed of scientists of that era were working. My central thesis here is that the formation of a distinctive research culture of open science was first made possible, and, indeed, was positively encouraged by the system of aristocratic patronage in an era when kings and nobles (both lay and ecclesiastical) were immediately concerned with the "ornamental" benefits to be derived by their sponsorship of philosophers and savants of great renown.[17]

My argument in support of this interpretation is that the economic logic of the patronage system in post-Renaissance Europe induced the emergence and promoted the institutionalization of reputation-building proceedings, all of which turned upon the revelation of scientific knowledge and special "expertise" among extended reference groups that included "peer-experts." Specifically, the core of this thesis is that the new departures from the ancient tradition of "keeping nature's secrets" were a functional response to heightened asymmetric information problems that had been posed for the Renaissance system of court-patronage of the arts and sciences. The pre-existing informational asymmetries between noble patrons and their *savants*-clients had been markedly exacerbated by the claims of Renaissance mathematicians and the increasing practical reliance upon new mathematical techniques in a variety of "contexts of application." Disclosure of both new knowledge and reliable techniques for solving

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[16] Following Webster (1970) and others in depicting the transformation of the conceptualization of science that occurred in seventeenth century England as the product of converging intellectual movements of reform, the work of William Eamon (1994) is notable for extensively documenting an "idealist" account of the mid-sixteenth century beginnings of the shift in the conceptualization of science away from that of the discovery and preservation of nature's secrets within an elect brotherhoods of scientists, and towards a new (Baconian) program of systematic pursuit and full disclosure of new discoveries and inventions. See David (2008: pp. 19-24) for a detailed critical examination of the evidence adduced by Eamon (1994: Ch. 10) in support that thesis.

[17] The broader significance of the support afforded to *savants* engaged in the new science by the system of private patronage during the late sixteenth and seventeenth centuries, has been noticed by Cohen (1994: p. 208) in a brief comment on Feingold's (1984: Ch. VI) emphatic contrast between the very few and limited places that the mathematicians of that era were able to find within Europe's universities, on the one hand, and, on the other, the employments that were made available to them as clients and tutors in aristocratic households. The mathematicians will be seen to figure importantly in the story told here.

practical problems offered a means for the mutual validation of claims to expertise; public challenges and competitions among the mathematically adept provided a convenient vehicle for building reputational renown. The mechanisms that eventually would be brought into service to meet that need spanned the range from the participation would-be *savants* in informal networks of correspondence, to public challenges and contests, open demonstrations, and exhibitions and the certification of individuals by co-optation and election to "learned societies."

No historical development of any consequence, and certainly no significant new institutional formation is likely to explicable by reference to a single cause. There usually are a multiplicity of factors and conditions that play a variety of contributory roles, some of which are enabling or facilitating of the new departure and therefore may be held to have been necessary even though they did not have a "precipitating" influence. Moreover, persisting alterations in specific social, political or economic arrangements emerge and acquire sustaining momentum from the confluence of forces that already are present in the social system, from the mutual alignment (and re-alignments) of the actions of individuals and groups, whose respective concerns and intentions may at their basis be quite different, but who find – or suppose – that their distinctive purposes will be served by making common cause with one another at least for the moment. The kernel of the present argument, however, is focused upon the configuration of precipitating causes, factors that in themselves may not have been sufficient to account for the changes, but whose addition to other, pre-existing (background) conditions enables us to understand why these institutional changes occurred when and where they did, and not earlier or elsewhere. [18]

Nevertheless, there were concurrent developments that, while not playing central explanatory roles, should be briefly recognized as factors facilitating or abetting more open discourse among those seeking to uncover Nature's Secrets, and the wider public circulation of information about their discoveries and inventions. Two set among these are

[18] To make a very simple illustrative point, it can be said that egotism and vanity are attributes that would impel mathematicians and scientists, like other peoples, to wish to call attention to themselves by displaying their learning and accomplishments for the admiration of others. But, were these basic human qualities to be proposed as having had an important role in the emergence of open science practices, one would have to ask why they had not come into play long before the latter part of the sixteenth century, and in some societies other than those in Western Europe. Similarly, Arrow's (2008) characteristically thought-provoking "Comment" on David (2008) – points to the exemplary sharing of knowledge by leading mathematicians in ancient Greece, and remarks that humans who possess highly specialized forms of expertise (such as mathematics) appear in an earlier time to have been motivated intrinsically by "the additional desires to acquire and to distribute information, above and beyond the values of economic reward and fame." True enough, they were without benefactors resembling the noble patrons of Renaissance Europe. But, what about the prospects of material support to be derived from the coterie of "youths" who gathered at the feet of thus-inspired (and renowned) teachers?

assigned auxiliary parts in the present argument, and therefore appear on either side of the core structure in the schematic, summary representation provided by Figure 2. On the Figure's left side, the prior development of the printing and publishing trades, following Gutenberg's innovations in the mid-fifteenth century, is recognized as a "background" condition that both both facilitated and created incentives for scientific authorship, and hence for the broader distribution of claims to new discoveries.

(Figure 2 here)

On the right-hand side of the Figure one finds acknowledgement that toward the close of sixteenth century the flowering of empiricism called for open demonstrations of experimental results, as well as displays of novel natural objects and artefacts; that this need could be accommodated by presentations before gatherings that included not only "scientific peers" but, importantly, members of local aristocratic elites, whose presence and patronage furnished social legitimacy and a measure of material support for the proceedings of the early "scientific academies, such as ."[19]

Patronage was an old system in the 17th century, and the sponsorship of intellectuals was a long-standing prerogative and responsibility of Europe's social and political elites.[20] It is necessary, therefore, to explain why something new appeared on the scene; why some of the conventions and norms now associated with open science – in particular, the reliance upon peer appraisal and collective evaluation expressed through the formation of professional reputations – were induced in primitive form at this particular juncture in history. The key propositions for this part of my argument derive from first considering the economics of patronage in general, and then noticing the specific implications of the newly arising problems of "principal-agent contracting" that were created by the encounter of the late Renaissance patronage system with the new

[19] Space is not available here to summarize extensive historical literature on the development and significance of the two sets of ancillary conditions that are identified in Figure 2, and considered in in some detail by David (2008: pp. 27-29, 70-75), specifically for the purpose of exposing the principal respects in which neither of them reasonably can be assigned a precipitating role in the transformations that of central interest here.

[20] On Renaissance statecraft and aristocratic patronage of art, architecture and public spectacles see Strong (1970), Hollingsworth (1996: Ch. 9).

(mathematical) form of natural philosophy practised by Galileo, Kepler and their contemporaries.[21]

Aristocratic patronage systems have reflected two kinds of motivation: the utilitarian and the ornamental. Most political elites, in addition to recognizing some need in their domain for men capable of producing new ideas and inventions to solve mundane problems connected with warfare and security, land reclamation, food production, transport facilities, and so forth, also have sought to enlist the services of those who professed an ability to reveal the secrets of Nature, and of Destiny. Kings and princes, and lesser nobles too sought to surround themselves with creative talents whose achievements would enhance not only their self-esteem, but also their public image – those aspects of grandeur and ostentatious display that might serve to reinforce their claims to rightful authority. Thus, poets, artists, musicians, chroniclers, architects, instrument-makers and natural philosophers found employment in aristocratic courts, both because their skills might serve the pleasures of the court, and because their presence "made a statement" in the competition among nobles for prestige. These dyadic patron-client relationships, which offered the latter material and political support in exchange for service, were often precarious, uncomfortably subject to aristocratic whims and pleasures, and to the abrupt termination that would ensue on the disgrace or demise of a patron. Nonetheless, they existed in this era as part of a well-articulated system characterized by elaborate conventions and rituals that provided calculable career paths for men of intellectual and artistic talents.[22]

Those motives for entering into a patron's role that reduce to symbolic acts of self-aggrandizement are here subsumed under the heading "ornamental." Such reasons, however, should be understood to have been no less instrumental in their nature and roots than were the utilitarian considerations for the patronage of intellectuals. The public display of "magnificence," in which art and power had become allied, was a stock item in

[21] See Moran (1991) for extensive discussion of the patronage of science and medicine in the court of Prince Henry of Wales (d.1612) at Richmond Palace, the Court of Rudolph II and the Habsburg circle in the mid-seventeenth century, the Munich Court of Ferdinand Maria, the Elector of Bavaria (r. 1654-1679), and elsewhere in Europe. Galileo's involvement in the system of court patronage in Italy and his communications during 1610 with Kepler, then in the service of Emperor Rudolph II in Prague, are treated in great detail by Biagioli (1993). On Kepler's services for less august patrons prior to accepting Rudolph's II invitation, see Thoren (1990:Ch. 12) and David (2008, pp.32-36.) The analogous situations of many notable scientific figures in eighteenth century Europe also should be mentioned, e.g., as in Mokyr (1990: pp. 73, 84, 169) on Leibnitz, Torriceli and Borelli, respectively.

[22] See esp. Biagioli (1990, 1993) and Moran (1991) for the sixteenth and seventeenth century patronage system's elaborate social conventions and rituals.

the repertoire of Renaissance statecraft. This is significant, because inventions and discoveries that met utilitarian needs in some instances would have to be kept secret if they were to be most useful, whereas it is in the nature of the ornamental motive that its fulfilment elicits the disclosure of new, marvellous discoveries and creations; that the client's achievement on behalf of the patron be widely publicized. Indeed, it was very much in the interest of a patron for the reputations of those he patronized to be enhanced in this way, for their fame augmented his own.[23] A second point of significance is that only some utilitarian services but most ornamental services had "positional" value from the patron's point of view. Although having a skilled artist or a clever astronomer in one's court was altogether a good thing; it was far better if such clients were personages of greater accomplishments and renown than those who happened to be in the service of a rival's court. The pressure on Europe's ruling families to have intellectuals of recognized eminence in their service was thus exacerbated by the existence of rival rulers and their courts, and so lent additional strength to the ornamental motives for their patronage of such clients.

Into this setting a new element had been interjected during the 16th century: the more extensive and rigorous use of mathematical methods formed an important aspect of the work of the new breed of natural philosophers.[24] But, one surely unintended side-effect of this intellectual advance was to render the basis of the mathematically sophisticated savants' claims and reputations less immediately accessible for evaluation by the elites in whose service they wished to be employed. The difficulties thereby posed by the asymmetric distribution of information were rather unprecedented, not having been encountered to the same degree in the patronage of intellectuals and artists who followed other, less esoteric callings. The new breed of scientists, however, claimed to specialize in revealing the unfamiliar. Opportunities for charlatanry here were more rife, and so were the risks of embarrassment for the patron, should it turn out that one had sponsored a

[23] Galileo understood this well, as was evident from the adroit way in which he exploited his ability to prepare superior telescopes for the Grand Duke of Tuscany, Cosimo II de' Medici: he urged his patron to present these to other crowned heads in Europe, whereby they too might observe the new-found moons of Jupiter which the *Sidereus Nuncius* (March 1610) had proclaimed to be "the Medicean stars." See Drake (1957, 1978), Westfall (1985), and Biagioli (1990, 1993: Ch.1, 2006).

[24] Following the fusion of Arabic and classical mathematics, the significance of algebra, the geometry of conic sections, trigonometry, and still more esoteric developments was recognized and openly proclaimed in terms that drew upon a rhetorical tradition reaching back to the great Renaissance mathematician "Regiomontanus" -- as Johannes Muller of Konigsberg (1432-1476) styled himself. See Swerdlow (1993), Boyer (1985: Ch. XV) on Renaissance mathematics; Keller (1985) on the program and rhetorical developed on behalf of mathematical training during the 1570's and 1580's; Feingold (1984:Ch.IV), Westfall (1985), Biagioli (1989, 1990, 1993) on the patronage of mathematicians.

fraud – or much worse, a heretic. Thus, even where the services of the mathematically trained intelligentsia might be sought for essentially practical, utilitarian motives (such talents being useful in designing machinery for public spectacles, surveying and cartography, ballistics and correct use of perspective in pictorial arts), the soundness of the candidates' qualifications had become more problematic and far from inconsequential.

In other words, this line of argument points to the emergence of especially compelling reasons for noble patrons in the late Renaissance to delegate part of the responsibility for evaluating and selecting among the new breed of *savants*, devolving those functions upon the increasingly self-aware communities of their fellow practitioners and correspondents. Except for those few who were themselves versed in mathematics or other experimental practices associated with the new learning, patrons were inclined to refrain from passing personal judgement on scientific assertions and involving themselves in substantive controversies. It was left to the initiative of those who were dependent upon such patronage to organize the production of credible testimonials to their own credibility and scientific status. Not altogether surprisingly, therefore, the mid-16th century, which is frequently taken as the beginning of the era of modern mathematics, also witnessed the formation of active networks of correspondence among Europe's adepts in algebra, announcing newly devised techniques and results; this era initiated the modern tradition of publicly posing mathematical puzzles, issuing scientific challenges, announcing prizes for the solutions of problems, and the holding of open competitions to test the claims of rival experts in the mathematical arts.[25] On the interpretation proposed here, the new practices of disclosure constituted a functional response to heightened asymmetric information problems that the mathematization of natural philosophy and the practical arts posed for the Renaissance system of court-patronage.

The conditions just sketched here regarding the late Renaissance and early modern system of court patronage presented a situation that modern economists describe as "common agency contracting" involving the competition among incompletely informed principals for the dedicated services of multiple agents. This correspondence suggests several noteworthy points about the economic organization of scientific activities in Europe during the late 16th and early 17th centuries. Firstly, because what the scientist-clients had to offer was "novelty," at any point in time the "interests" (or welfare) of

[25] On patron's self-restraint from expressing personal judgements on scientific claims, *see* Biagioli (1990, 1993) -- excepting the extraordinary cases of mathematically proficient princes discussed by Rose (1977) and Biagioli (1989). On the emergence of open competitions among mathematicians, see Boyer (1985: esp., 310-312), Feingold (1984), Keller (1985), and further discussion in David (2008: pp. 46-49.

several patrons could not be jointly advanced in the same degree. In other words, as a consequence of the dominance in the early history of modern science of patrons who were concerned with the ornamental rather than the utilitarian value of scientist-philosophers, the services that a client provided to his several patrons were essentially "substitutes" rather than "complementary" goods.

Secondly, in the majority of cases the material rewards offered to clients by any single patron were not sufficiently large and certain to free the former from the quest for multiple patrons. The situation typically being that of common agency, we may draw on the results of economists' game-theoretic analyses of this form of interaction among principals and their client-agents.[26] This tell us that when the patron-principals cannot act in concert, and lack full, symmetrically distributed information concerning the agents' respective efforts and costs, the incentive contracts offered to clients generally will be insufficient to adequately support a client that has only a one patron. This outcome reflects the principals' awareness of the possibility that a client/agent could use the means provided by one patron to serve the ends of another. The resulting Nash equilibrium in the game among rival principals would then be a set of patronage-contracts that offered clients comparatively "weak" material incentives to devote their efforts exclusively to the service of any one patron. Such a state of affairs, of course, would be consistent with the necessity of seeking to serve a number of patrons concurrently --however arduous and demeaning a scientist like Galileo might feel that to be.[27] It thereby would reinforce the choice on the part of would-be clients of research and publication strategies that would lead towards widening the circle of their repute.

Thirdly, as has been shown by the growing literature devoted to analyses of economic mechanism design under conditions of common agency contracting, the

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[26] A more detailed treatment of the proposition in this and the next paragraph will be found in found in David (2008: sect. 5.1—pp xx-xx), which draws principally on Stole (1990) and the review provided by Dixit (1995). The literature on common agency games is now quite extensive, having expanded rapidly in many applied directions, including some that have a bearing on the equilibrium terms of patron-client contracts that are of interest here. See, e.g., Olsen and Torvisk (1993, 1995) common agency mechanisms and organization design; Lausel and Le Breton (1996) on the conditions for existence of positive "rents" for the agents in private common agency arrangements under complete information; Dur and Roelfsema (2010), on social interactions arising from principals' competition for the attentions of agents.

[27] In a letter written to a Florentine courtier early in 1609 by Galileo, a passage --translated by Biagioli (1990: p.130 -- makes it plain that he regarded a career serving many low status patrons for piecemeal compensation to be *servitu meretricia* – a cheapening, "harlot-like" employment. According to Biagioli this expressed Galileo's view that the degree of social legitimation offered by the patronage one received from many minor patrons "could not be compounded to the equivalent of that which a great single patron would afford", even were the material benefits bestowed by the latter were to be matched by the aggregate of the modest material support received from each individual in the former multitude.

equilibrium outcome in the case of "contract substitutes" is in general more favourable to the agent than is the case when the services performed for different principals are complements. In effect, the competition among patrons to command the faithful attention of an agent/client would lead to contracts that allowed the latter to retain more "rents" from the specialized information he possessed. This provided greater rewards for scientific activities than would have resulted otherwise, were there only a single possible patron on the scene, or had the patrons predominantly enjoyed positive externalities from others' support of the agent's efforts – the characteristic situation where there are significant "spillovers" of utilitarian benefits from new knowledge.

There is in the story related here an historical irony well worth remarking upon, especially as it serves also to underscore the tenacity of the past's hold on the incrementally evolving institutions that channel the course of economic change.[28] The nub of it is simply this: an essentially pre-capitalist, European aristocratic disposition to award patronage for the purposes of enhancing rulers' political powers symbolically -- through displays of "magnificence", came to confer value upon those who pursued knowledge by following the "new science" in the late 16th and 17th centuries.

A vital but fragile institutional legacy of European feudalism

The norms of cooperation and information disclosure within the community of scientists, and their institutionalization through the activities of formal scientific organizations thus emerged (in part at least) as a response to the informational requirements of a system of patronage in which the competition among noble patrons for prestigious clients was crucial. Likewise, the initiation of State patronage of scientific academies was propelled as much by the ornamental motives of absolute monarchies as it was by an appreciation of the new knowledge as a potential foundation of wealth and power.[29] These monarchical institutions -- echoing the former rivalries among the noble houses of the principalities that they had absorbed – thus passed into the nation-states of early modern Europe. Their preservation in re-adapted, attenuated and outwardly altered forms rendered them a part of the enduring legacy of fragmented political authority that had been created by western European feudalism. Furthermore, this evolving institutional

[28] On the theme of "path dependence" in the dynamics of economic systems, see, e.g. David (1988, 1994, 2001, 2007).

[29] See David (2008: sect. 5.3, esp. pp.77-81) on the evidence against the contentions that in France the emergence of state-patronage for science in the form of the royal academies, was a consequence of the greatly increased costs of the new scientific pursuits – the so-called "Fontenelle Thesis."

heritage carried with it the economic logic of conditions of *common agency contracting in substitutes* that characterized the relations among clients and patrons during the late Renaissance.

An illuminating and contrasting comparison therefore might usefully be drawn between the western European experience, and the quite different course of institutional history that unfolded in the alternative circumstances of a monolithic political system such as had prevailed in the Heavenly Empire of China. It has been stressed that in the absence of any comparably dominant single principal-patron, the multiplicity of Western Europe's contending noble courts created conditions that were more favorable for the agent-client members of the scientific community. This was so both in terms of the "information rents" they were able to retain on their specialized knowledge, and their collective development of greater professional autonomy. That aspect of the argument advanced in the foregoing pages affords comparative historians of science and technology a fresh perspective on the well-known paradoxical observation that, despite the remarkable record of scientific inquiry and technological accomplishments produced in China during the Sung Dynasty (960-1279 C.E.) -- and richly documented by Joseph Needham (1954-2008) and his collaborators, the "Scientific Revolution" that emerged three centuries later was a distinctly West European cultural product.[30]

Viewed from that angle, the critical institutional side of the scientific revolution of the seventeenth century -- which saw the pursuit of new knowledge carried on under the patronage of rival political authorities at numerous geographically dispersed and culturally diverse courts and academies -- contributed not only to the flourishing of science, but to preservation of the advances that had been made in the accumulation of reliable knowledge upon which further research could build. The existence in Europe of an extensive contiguous territory, over which political power was decentralized to multiple,

[30] Needham (1969) posed the problem of why it was that although Chinese civilization had been "more efficient than 'occidental' civilization in applying human natural knowledge to practical human needs" between the first century B.C. and the fifteenth century A.D., in the centuries that followed it was Western Europe that emerged as the technologically and industrially more dynamic society. Needham's answers to this question, however, came to focus more on issues of class and culture, than on political structure. For all its rationalism and organizational effectiveness in its early stages (from the 4th through the 8th century), China's Mandarin bureaucracy later came to obstruct scientific undertakings and could not make up for the lack of a "mercantile culture" that he saw as the core of Europe's capitalism and expansionism. See Cohen (1994: Chs. 6.3-6.5) on the problem of the non-emergence of the 16th - 17th century Scientific Revolution in China; Mokyr (1990: Ch. 9, esp. pp. 228-238) on the different, so-called "Needham problem" -- why the Industrial Revolution of the 18th century did not happen in China. Neither of these surveys focus on the contrasting legacies of Western European feudalism and what Needham (1985) referred to as China's centralizing "bureaucratic feudalism," and the implications of that difference for the Scientific Revolution that are considerd in David (2008: pp. 85-88).

contending centers of authority, was a distinctive and historically contingent product of region's cultural and political history. The logic of vassalage institutions in the medieval epoch had given rise to a political landscape of fragmented and contending principalities, each governed on the basis of personal authority. The fragmented structure of political authority in Renaissance and early modern Europe had the effect of providing the *protection of statistical independence* from the workings of the variety of systematic forces and exogenous disturbances to order that could interrupt the advancement of science in any one place and time, and that often had done so. By the same token, the practices of open science that developed within the European political and social context were conducive to maintaining the exchange of information through radiating networks of distributed and intellectually variegated actors. These networks of scholarly communication, whose nodes initially were situated in the courts of Renaissance nobles, stimulated and imparted sustaining momentum to the cumulative, transformative process that uniquely characterized the advancement of science in that part of the world To put this point this point baldly, it may be said that the emergence of the characteristic institutions and organizational features of open science – which have played so vital a role in generating the sustained material achievements of the era of modern economic growth – were western Feudalism's greatest gift to Capitalism.

Rather and having emerged and survived as useful epiphenomena of "mechanical philosophy," a new *organum* of intellectual inquiry, the institutions of open science are thus seen to be independent and in some measure fortuitous social and political constructs. They are cultural legacies of European history that continue profoundly to influence the modern systemic efficacy of the scientific research process. Being in some significant degree exogenous to actual scientific practice, these features of the institutional landscape in the world's representative democracies can be subjected more easily to substantial re-design, or otherwise manipulated as potent instruments of science and technology policy. This is both a good and a worrisome thing. Wise and forward looking policy-making for this sensitive part of the modern institutional infrastructure will need to grasp the complex and contingent character of these organizational instruments' evolution, and therefore respect the potential fragility of the institutional matrix within which modern science has flourished.

Open science norms and institutions are a relatively recent social innovation whose workings must be continually re-created as "social facts". This regenerative process depends upon the scientific practitioners themselves recognizing that much of the "power" that their research communities possess for the successful pursuit of reliable knowledge derives from their personal appreciation of and commitment to behaviors that conform broadly to the informal "cognitive norms," as well as to the formal regulations governing their activities. In short, the sustained functionality of these vulnerable institutional legacies ultimately rests not in the hands of some distant, unknown and hopefully wise designers of public policy, but upon scientists' acceptance of responsibility for day-to-day individual and collective actions in support of "good scientific conduct conjoined with good technique," and for transmitting that ethos to the future scientists who look to them as mentors.

Sustaining the future vitality of open science: challenges and responses

Recent experience shows the importance of that imperative. The past two decades have witnessed the emergence and flowering of effective responses to the challenges that during the 1980's and 1990's appeared to seriously threaten the continued vitality of open science research in the public interest. Beginning as a reactive awakening among researchers in particular scientific domains, this movement gradually attracted broader a broader and more diverse following, and soon drew encouragement from some quarters of the social sciences, as well as important constructive initiatives from legal scholars who shared the scientists' worries about the *de facto* drift of science and technology policies in the West towards securing opportunities for near-term commercial exploitation of publicly funded research results. As will be seen, they ought not only statutory reforms, but more immediately available legal mechanisms that could be deployed to mitigate the potential for long-term societal and cultural harms to flow from unchecked transformations of the sort that were taking place in the international regime intellectual property rights protections.[31]

The following pages briefly reviews those developments, focusing first on the nature of perceived threats that were found to be especially worrisome for fundamental advances in scientific knowledge, and then turning to highlight several particularly noteworthy aspects of the countervailing responses what were mobilized from various elements of within national and international academic science communities.

Because it may be both an instructive and a promising sign for the future sustainability of open science institutions, the general observation that deserve emphasis

[31] See Maskus and Reichman (2005: Ch. 1 (on "The globalization of private knowledge goods and the privatization of global public goods," by the editors of this compendious work).

in this concluding section's limited space is simply this: significant and effective remedial action was possible without (and possibly because) the scientific issues at stake did not become publicly politicized. Instead, reactions to perceived threats to the effective and efficient conduct of exploratory science came initially from within the West's leading research universities. Those varied expressions of alarm, and some among the proposed defensive responses, elicited crucial reinforcement from the leadership of national government agencies that had direct responsibilities for the allocation and regulation of public research funding, especially the agencies, ministries, institutes that systematically drew upon distinguished members of the relevant research communities when filling top-level administrative positions. Eventually, as promising models for corrective national policy action became more frequent and visible, and so lent themselves to general recommendations illustrated by successful concrete implementations, international organizations (such as the OECD) issued codified "principles and guidelines" for protecting researchers' wide and easy access to high-quality scientific data and information that had been generated by publicly funded projects. Those recommendations, in turn, became more widely disseminated through their implementation in the regulations of the U.S. and other national governments, and the announced policies of major private foundations that were patrons of scientific research. [32]

To quickly take up the thread of this story closer to its beginning, one may recall that even though the transformative impact of the enormous potentialities for practical application and further augmentation of scientific and technical advances in digital information technologies and biotechnology were already incipient, and grasped by the participants during the 1970's, it was not until the 1980's that their unanticipated and disruptive impacts began to touch the institutional infrastructure supporting the conduct of publicly funded scientific research. The ramifying industrial *sequelae* of those technological advances and raised the strategic value for businesses in both domestic and international markets of stronger, and more readily enforceable legal protections that could be afforded to holders of intellectual property rights. Along with losses of previous dominance in the markets for durable manufactures, this heightened concerns in leading western government circles about possible future threats to their economies' competitive advantages in information-intensive and bio-medical product markets.

[32] The following text draws freely on David and Uhlir (2007) and the author's policy-oriented publications (cited in the Prologue, esp. footnotes 3, 4, 8 (above).

The resultant government efforts to favorably adjust domestic and international IPR regimes, combined with budgetary pressures to curtail public expenditures for scientific and engineering research, abetted by other transient circumstances (some of which already were noticed in the Prologue), produced a marked shift in the structure of national research policies. This movement was in the direction of further "commodification" of science, and gave greater weight to near-term "market valorization" (rather than long-term "social valorization") in assessing the likely pay-offs for tax-supported "applied research." Correspondingly, the relative share (and in some cases also absolute levels) of state support for exploratory, fundamental science, and long-term mission oriented R&D programs at academic institutions and civilian government institutions and foudations. s. The alterations of the locii and directions of public R&D support for science and technology in the U.S. and the EU during that era remain evident to this day.

Furthermore, the legal protections now afforded to private property owners under the copyright regime now extend far beyond the arena of printed texts and images. They potentially cover all forms of data and information that can be digitally inscribed, and in some national and regional juridictions s*ui generis* intellectual property rights protections have been created by novel statutes and for the benefit of parties that have invested in the construction of databases containing all manner of information (including "works of low authorship") and whether these are copyrightable or not. Similarly, the patentability of inventions and discoveries now is construed more broadly, especially in the U.S., encompassing claims to information that formerly would have been deemed "facts of nature" and hence ineligible for protection; patents are issued on an unprecedented scale to inventors of tools and techniques in many research fields, and particularly in the biomedical and computer sciences, but at the other end of the spectrum to "business models" implemented by computer software.

Technical information that in former times would be likely have been left in the public domain now tends to be swiftly appropriated as intellectual property, unless special measures are taken to thwart such "privatizing" actions. This is not necessarily done in anticipation of significant streams of revenues flowing to the possessor as a result of the demands by other for its use, but, instead, patenting is seen by business companies to have potential value as a defensive (or aggressive) instrument to be deployed in future patent licensing negotiations, or in litigation arising from infringement suits.[33] Moreover, restrictive licensing practices and increasingly effective "digital rights management" technologies combine to provide additional layers of "enclosure" beyond those conferred by the transformed regime of intellectual property rights protections.

Even as prospects for the new legal and technical foundations of "intellectual capitalism," were being enthusiastically embraced in some entrepreneurial quarters, and envisaged in rather sanguine academic writings,[34] this movement; troubling collateral developments were attracting adverse attention. The creation of new legal property rights and enforcement mechanisms for digital technology-based innovations in information goods markets, while often rationalized in the name of scientific and technological progress, increasingly was seen to have been promoted by commercial interests for other, special purposes. In some quarters of scholarly publishing (as in other branches of the media industry) incumbent firms sought extended and more strongly enforced global copyright protection in order to stabilize traditional business models by blocking incursions by new entrants' pursuit of disruptive business strategies.

These developments impinged also on the sphere of academic and other public research organizations, noticeably first affecting libraries' online subscription costs. In the U.S. under the Bayh-Dole Act (1980), research universities -- having been permitted to seek patents for discoveries and inventions resulting from their conduct of federally funded research – were actively filing for and receiving patents on technical advances in the frontier areas of biotechnology and computer hardware and software, as well as software copyrights. Where the discoveries and inventions in question were basic research tools that had open wider opportunities for further investigation, key patents on elements in the basic tool sets of those frontier areas gradually began to be recognized as potential impediments to future advances (including important applications) that called for collaborative research.

Moreover, the alteration of institutional and individual incentives under the Bayh-Dole regime were belatedly recognized as having exacerbated the powerful incentives that the reputational reward system of open science itself creates for researchers to allocate all

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[33] See David (2007b), for further details regarding this perspective, and references to the literature on the transformations in the nature and economic significance of the patent (and copyright) systems that took place during the past quarter-century.

[34] See Grandstrand (1999) for an uncommonly thoughtful examination of the concept and material foundations of "intellectual capitalism" as a techno-institutional construct, and a guarded but generally welcoming appraisal of this emergent phenomenon as a new and a promising future stage in the evolution of market- driven capitalism.

of available resources of their current projects to speeding the production, checking and write-up for publication of its novel and striking findings, upon which to ground claims for priority of discovery or invention, rather than spending time on transparently documenting and making the those findings available for the use of other scientists in the same field or research domains. To do otherwise would risk sacrificing the possibility of enhanced peer esteem, and the attendant ego-gratifying flow of material rewards, and greater likelihood of future competitive successes in securing continued research funding. This conflict between the priority-based reward system of open science, and its ethos of cooperation in the collective pursuit of reliable knowledge – which Merton saw as a source of "neurotic tension" for those working within such a system – was sharpened where funding was more tightly restricted and exploratory science projects faced severely binding resource constraints.

Unfortunately the latter only worsened the long-standing reality of public agencies' policies in regard to civilian scientific research programs, which systematically under-funded activities such as data documentation and curation, and transparent description of research procedures, tasks that are best be carried out by those directly engaged in the research itself. Without adequate support being explicitly provided for rapid, high quality documentation and responses to request to share research materials and tools, project directors are unlikely to divert limited project resources to helping external peers (including known or potential rivals in the field) to quickly replicate, assimilate and exploit the conceptual and material tools that their latest results would provide.

Whatever stimulus the Bayh-Dole Act had imparted to increasing applied, commercially oriented research in universities and publicly funded research institutes, the institutional re-orientations following in its train also brought unintended and interrelated impacts that were detrimental to continued efficient academic science collaborations aimed at advancing research explorations in frontier areas. By creating new incentives for maintaining secrecy while racing for priority in obtaining research results on which stronger legal protections for valuable intellectual property rights could be secured by publicly funded institutions, it exacerbated the conflict that already existed between the cooperative norms of open science, and the latter's reputational reward system based on validated claims to priority in new scientific discoveries and inventions. Combined with the chronic under-funding of grant support for disclosure of transparently documented data and technical information about details of the research processes underlying published findings, these altered incentives work to further lengthen publication lags (while patent applications were filed), and increase non-cooperative behaviors in response to requests to share research information, data and materials.

Interposing legal impediments to sharing scientific and technical information and data, and introducing additional incentives for rapid disclosure of new methods and findings t reinforced the "natural" tendencies of researchers to "keep going" when their effort are yielding interesting results, rather than pausing to document and render transparent for others the steps that them to that happy state. The incentives created by the open science reward system itself works to reinforce such choices concerning the allocation the human resources provided to the project by its grant funding. Sacrificing other desirable activities to speed the production, checking and write-up of novel and striking results is a decision that follows directly from importance of being able to claim priority of discovery, attested to by priority of publication. For, that is the key requirement of the reputational reward system based upon (scientific) peer esteem, and all the ego-gratifying and material benefits that a research may wish to derive therefrom – among which the enhanced probably of successes in future competitions for research funding surely will be a prominent consideration.

Without adequate additional support being explicitly provided for rapid, high quality documentation, research projects are unlikely to divert their limited resources to activities that are likely to help others (including rivals in the field) quickly to replicate, assimilate and exploit the further implications that may flow from their project's fresh findings. The "Bayh-Dole reorientation" of institutional incentives, by adding to the attractions of racing for priority in obtaining research results on which stronger and more valuable intellectual property rights could be secured, thus intensified a recognized pre-existing conflict between the role that priority of publication played in the reward system of open science and the latter's the cooperative ethos, as well giving rise within the academic research environment of new, legally protected and institutionally sanctioned impediments to the sharing of new information and the collective advancement of scientifically reliable knowledge.

Academic scientists working in physics, astronomy, atmospheric and molecular chemistry, and the mathematical sciences, were especially quick to register alarm about about the possible damages that could result from the incursion of intellectual property rights claims. Those were fields characterized by strong traditions of international cooperation and collaboration reaching back to the early twentieth century; where it had long been presumed that technical information and data about the observational instruments and techniques that had enabled discoveries of "facts of nature" should be left in the public domain --along with the discoveries themselves.[35]

Elsewhere in the universities, however, a new set of opportunities and accompanying tensions were emerging as an unintended result of government "reforms" inspired by the Bayh-Dole Act (1980), one effect of which was to bring into existence within the academic institution a dual system of rewards for faculty researchers in science and engineering departments, in which the two constituent systems' respective effects on transparency and sharing of research information and data were largely inimical. The patent system's social value stems from the incentives it offers inventors for their rapid public disclosure of novel and practically useful ideas -- in exchange for legal rights to the exclusive exploitation of the inventions in question. The quest for that potentially valuable asset, however, tends to induce secrecy about the specific purposes and technical aspects of the research process, as well as encouraging later obfuscation (to the extent possible in patent applications) of some critical details as to how a licensee other than the inventor might best obtain the useful results promised by the patent that had been awarded.

Consequently, unprecedented tensions and occasional open conflicts arose among departmental colleagues– notably in departments of computer science, molecular biology and genetics, where the frontiers of research were advancing rapidly and new scientific findings could be quite readily recast as commercial innovations. For those who were attracted by the latter prospects, the university's newly apparent interest in patents on publicly funded research results was sufficiently appropriate warrant for them to take steps to maintain secrecy about their ongoing research projects (and to tightly restrict

[35] The view widely held in these fields prior to WWII -- that it was "inappropriate" to patent scientific discoveries and inventions that might have important practical applications – also was strongly supported by that era's major *private* patron. The Rockefeller Foundation, through its general policies and the funding decisions of its Natural Sciences Research Division, beginning in the 1920's, played a critical role in advancing research, e.g., on the chemistry of toxins and antibiotics (most notably, penicillin). See Jonas (1989), and Lax (2005). It is noteworthy too that in the domain of genetics and genomics, the Human Genome Project that was taking shape in the latter 1980s (and formally launched in 1990) had modelled itself on the Big Science projects in particle physics and astronomy, not only with regard to its international scope and time horizon, but also in the HPG's resistance (under first director, James D. Watson) to pressures to patent fragmentary gene sequences – which led to Watson being fired by the Director of the NIH. Subsequently, the HGP, with the important backing of the Wellcome Trust in the U.K., adopted a policy of daily disclosures of its data on new sequences. That stance was publicly endorsed in 2000 by President Clinton's announcement that when HPG's sequencing of the genome would be completed, the results would not be patented and the data would be made available for use by all researchers, setting a model for publicly funded scientific research projects in biogenetics, genomics and proteinomics. See, Sulston and Ferry (2002); also http://en.wikipedia.org/wiki/Human_Genome_Project; http://www.genome.gov/10001763.

access to proprietary data that had been supplied for their use by cooperating industrial firms). Such actions would be entirely normal in a large and well run corporate lab, where securing patents was commonly understood to be the *raison d'etre* and urgent proximate goal of the variety of R&D projects that typically would be under way concurrently.

But, in the U. S. academic context, some faculty researchers viewed such behaviors as seriously breaching both the spirit and the customary practices of scientific cooperation, which presupposed their colleagues' willingness to reciprocally exchange knowledge about research problems and their possible solutions. Moreover, it signified the casual abandonment of collegiality in pursuit of another, defining common purpose of the university's faculty.[36] Whatever socially useful ends might be served by the research knowledge gained, and the patents to which it lead might serve, the process of closely guarding both had restricted communications between and among the graduate students and post-doctoral fellows who were engaged on such projects, and the rest of the department's students, as well faculty members who took no part in them.

In addition to these intra-departmental issues, new and increasingly time-consuming foci of conflicting interests emerged elsewhere within the research universities, having been created by the prospects of revenues that might become available to some departments and schools from sales of patents and copyright licenses, or their exclusive licensing to business firms -- let alone to the equity that the institution might hold in faculty-research based start-up ventures. A whole new world of institutional level conflict-of-interest problems awaited acknowledgment and recognition. In the U.S. research universities, the issues thus raised were felt most palpably by the administrative leaders responsible for decisions about new faculty and staff appointments and promotions, as well as for allocating space and research facilities that were funded by research grants over whose results the university might assert intellectual property ownership.[37] But, by

[36] See, e.g., Owen-Smith and Powell (2001) on tensions within the Biology Department at Stanford University. Still more seriously, placing restrictions on the freedom of student research assistants and post-docs to consult any member of the faculty and discuss their work with fellow students was seen more generally by faculty members and university leaders as potentially threatening the institution's educational purpose. More specifically, it was at odds with widespread commitment to conduct important aspects of the graduate science and engineering training in the context of on-going research projects" whose work was open for discussion among students and between students and their professors – a distinctive feature of America's research universities that (rightly) was held to be a major factor contributing to their effectiveness and international prestige..

[37] The Bayh-Dole Act of 1980 and its *sequelae* compounded the already complicated hierarchical structures of governance and resource allocation processes that was typical of major U.S. (private and public) research universities. Discussions of this and some related issues pertinent to the American institutional context can be found in the contributions to American Academy of Arts and Sciences (1993), and David, Mowery and Steinmueller (1994) – with particular focus on issues arising in university-industry research relationships. David

the mid 1990's, expressions of growing concern at the national level among science policy analysts had been prompted by the visible commoditization trends in scientific publishing, as well as by the unprecedented degree to which academic patenting was being extended to fundamental research tools in computing, biomedical science and nano-technologies. Other, still more surprising and disconcerting expressions of discontent with the new regime on the part of corporate vice-presidents of research, would take somewhat longer to surface publicly.[38]

Many complex policy issues are encountered in attempting to arrive at a proper balance between the benefits and drawbacks of privatization and commercialization of data and information, especially as these affect public-sector science. Similar "trade-offs" arising in making decisions about the imposition of government "security restrictions" upon certain lines of research.[39] These policy quandaries resist quick and simple solutions at the societal level. When they arise from a multiplicity of conflicting purposes and associated reward systems within the same organization, the understandable internal political pressures to resolve them by compromise is likely to compromising the effectiveness with which many among those purposes can be served, and this holds for government agencies no less than for academic institutions. An awareness of the likelihood of such outcomes was a significant factor motivating the "bottom up" initiatives on the part

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(2001b) examines parallel problems that were manifesting themselves some years later in the context of publicly funded research universities in the UK.

[38] See, e.g., Hertzfeld, Link and Vonortas (2006) for findings from a survey of executives from 60 major R&D intensive U.S. corporations, which present a decidedly unflattering contrast between their experiences in patent licensing negotiations with university representatives, and comparable negotiations conducted with other business firms. David (2006: pp. 267-271) confronts European misapprehensions and expectations with the quantitative record of the 1985-2005 performance of the Bayh-Dole regime in stimulating and 'transferring' new technologies for commercial exploitation by U.S. companies.

[39] In 1999, responding to "a request from several federal science agencies" in the U.S. (concerned about the potential outcome of legislative proposals for legal protection of database rights introduced in the U.S. Congress following the EU Directive of 1996), the Commission on Physical Sciences, Mathematics, and Applications of the NAS, the National Academy of Science for a National Research Council Study Committee – tasked to "identify, examine and evaluate the various existing and proposed policy approaches [for] Promoting Access to Scientific and Technical Data for the Public Interest." See: National Resource Council (1999). The interest of the government "science agencies" was reflected not only their initiation of the request (and quite likely in funding the Study Committee's work).It may be inferred from the concentration of their personnel among the participants in the January 14-15 Workshop held in Washington, DC to obtain "broad input from representatives of the main identified interest groups." Each of the following organizations was "represented by 4 to 6 individual participants in the Workshop: National Institutes of Health, National Science Foundation, National Oceanic and Atmospheric Administration, U.S. Geological Survey, National Institute of Standards and Technology. The Committee's report (NRC 1999:pp.10-12) recommended "Legislative Principles" for any new statutory protections of proprietary rights, in order to curtail the damage to public interests that could otherwise ensue from further restriction of access to scientific and technical data. The thrust of the recommendations for government policy actions (pp.12-13) was that data owned or controlled by the U.S. government should be disseminated for not-for-profit and commercial uses by all users on a non-exclusive basis, and made available at the marginal costs of its reproduction and distribution.

of academic scientists who undertook 'to devise appropriate means of protecting the culture and practices of open science at levels that were more immediately under their governance and future control.

That this undertaking also proved to be feasible does not seem so remarkable – when considered in retrospect. Researchers in modern public science and engineering organizations were at the forefront of many of the basic technological advances that underlay new paradigms of digitally networked information creation and dissemination activities:- high-speed mainframe computers and packet-switched digital data networks with large bandwidth, the TPC/IP protocols of the Internet and the World Wide Web, and still later innovations supporting Grid computing and Web-based middleware platforms facilitating interoperability in distributed computing and data storage, and providing ubiquitous access to those and other services "in the clouds." From these and other remarkable tools that scientific workgroups fashioned, re-or-less as research "by-products" in order to solve to the ever-pressing practical problems (of computation, communication, and data capture and retrieval) that are recurring encountered by projects committed to pushing the frontiers of knowledge, had sprung a wide array of the Information society's" enabling technological elements. It is an irony of history that through the impetus thereby imparted to mutually reinforcing technical, institutional and market transformations, the unintended ramifications of "gifts" from open science communities came back upon them –like a surprising blow from a returm boomerang – in the "enclosure" (as legally protected intellectual property) of swaths scientific data and information, and software tools that researchers formerly expected to find at their disposal in the public domain.

The response mounted by scientific research communities throughout the world in response to that dismaying trend, which in the course of the 1980's became increasingly palpable for some among them, took shape in numerous, specific defensive actions accompanied by the formulation of supporting rationales. To protect their accustomed ways of "doing science", a new array of tools and procedures were devised to facilitate the creation of *sustainably available* digital information resources. These have included institutionally hosted repositories for scientific pre-prints, journal articles and educational materials, "open access" electronic journals published with the support of universities and not-for-profit scientific organizations, public-domain digital data archives and federated open data networks.[40] Moreover, new and more efficient tools were fashioned, with which to pursue the research results that would thus be made more readily accessible: open-source software systems, and middleware platforms that permitted remote operation of diverse observational instruments whose output-streams could be linked to high-speed data analysis and real-time simulation capabilities, are now basic components of the "cyberinfrastructure" for research scientists and engineers. These are complemented by the rapidly growing toolset for achieving and maintaining high reliability in the evolving bodies of specialized software code and data --beginning with client-server version control systems for distributed development of software algorithms, and automated mirroring of distributed correction and annotation of datasets. Created to address the needs of research, these technical innovations have yielded beneficial "spillovers' for other forms of collective pursuits whose creativity is similarly enhanced by open, distributed collaboration.

The growing awareness among publicly funded researchers of the socially important functional roles played by specific, institutionalized open science practices, fortunately, has not spared these from periodic searching evaluations and some sharp criticism within the academic science community. Peer-reviewing of research contributions submitted for journal publication, has been one such practice that early in the eighteenth century already was drawing criticisms within England's Royal Society -- well before that practice became institutionalized and widely established with the professionalization of scientific research during the latter half of the following century. Today it remains a perennial subject of complaints and proposals for reform. A noteworthy recent case in point is the systematically documented critique in the pages *Science* of the unanticipated degradation of the performance of peer-review, and generally poor standards of journal editing that has accompanied the explosive growth of predatory profit-seeking "open access journals" in the worldwide enterprise of scientific publishing.[41]

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[40] Here it may be useful to be specific: e.g., among prominent U.S. open data centers and archives: GenBank, the Protein Data Bank, Space science data centers; among the federated open data networks: World Data Centers, Global Biodiversity Information Facility,NASA Distributed Active Archive Centers; among publicly supported non-subscription and non-profit open access (OA) journals: BioMed Central, Public Library of Science (PLOS), +and 65% of the c. 2500 current nominally "open access" scholarly journals); among open institutional repositories for publications in a major subject areas: (PubMedCentral, arXiv.org (physics) e-Print Archive.

[41] Bohannon (2013) documents the shocking abandonment of editorial quality control and peer-reviewing standards among the growing fringe of new ("predatory") OA journals—business enterprises that are in effect publishing un-reviewed material in exchange for authors' payments. In some cases these new journals appear under under the aegis of major scientific publishing firms with strong reputations derived from their other (separate) lines of high-quality journals.

This, of course, is but one among the problematic aspects of the actually workings of institutions formed in the evolution of open science, and hardly alone in warranting serious remedial attention and mechanisms for better governance .[42]

Institutional and organizational creativity has gone hand-in-hand with technological initiatives supporting open access and efficient search and retrieval of information and data resources. Perhaps the most familiar and immediately consequential instance of the parallel institutional response from scientific communities is seen in the reflexive relationship between the "open source" and "open access science" movements of the past quarter century. The norms and practices that had been widely established among U.S. university-based scientific research projects during the post-WWII decades were key progenitors of the emergence and startling competitive success of "free and open source software." During the 1990s Apache, Linux and other emblematic software development communities emerged with new new tools for creative collaboration that were used by large numbers of volunteers in distributed peer-production organizations that rapidly released (and debugged) successive versions of their code.[43] The practical viability of these large projects rested heavily upon the "copy-left" clause of the General Public License (GPL-GNU), under which, typically, their software products were released. "Copy-left" licensing, in effect, re-purposed the protections afforded to individual holders of software copyrights by utilizing contract law to construct a de facto "commons" within which new bodies of code, and subsequent modifications, extensions and adaptations for novel applications could continue to shared freely with others.

This particular way of licensing copyrighted material, making the source code of computer programs available on a royalty-free basis for use by the licensee's non-commercial purposes, and redistribution to others on the same terms, was an innovative contractual mechanism devised by Richard Stallman and other expert programmers who joined him in pioneering the free (and open source) software movement.[44] They had trained and worked in academic research settings during the 1970s, where, in accord with the still-prevailing norms of academic (open) science projects, the code they wrote for computer operating systems and applications was left in the public domain. Subsequently,

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[42] For discussion of sources of inefficiency in the open science reward system, and other important problems of socially sub-opitimal resource allocation affecting academic research, see Dasgupta and David (1994: sects. 5-6).

[43] See, e.g.,Benkler (2002, 2006); Feller et al. (2005).

[44] See Stallman (2002); http://en.wikipedia.org/wiki/Free_software_movement, and references therein to the founding role of Stallman's GNU project at MIT in 1983.

however, some among those programs were taken up, re-expressed and copyrighted by commercial software vendors in the early 1980's who were charging high prices for their mass-marketed products, and selling them under terms that prevented the users (including the programs' original authors) from making further modifications of any kind without first obtaining a costly, and rarely granted copyright license for the source code.[45] Stallman chaffed against the legal restraints that had been placed upon his own freedom, and that of others to build new and better software tools by further developing their own previous work. Moreover, he went beyond public denunciation of this state of affairs, and took the initiative of responding constructively (in a double sense) creating GPL-GNU license, using it to release his software, and promoting its wider adoption. .

For natural science researchers in particular, the sudden advent of open source software, and the recognition of its roots in the traditional code-sharing practices of academic science, had the effect of reifying the idea of "open science" as a form of "self-help" to secure continuing access to the digital research tools that regarded – -along with many new scientific instruments as "natural by-products" of the research process. This conscious "cultural re-connection" is evident in the records that survive on the Web from a conference organized at the Brookhaven National Laboratory on October 4th, 1999, under the title "Open Source/Open Science". It was the first prominent public scientific occasion (according to organizers' claim, the present author's knowledge) at which the term "Open Science" was used —albeit not with any of the broader institutional connotations that those words term now convey.[46] Although the term in its presently accepted sense gradually came into use in academic publications on science and technology policy during the 21st century's opening decade, well more than another ten years passed before its next appearance on a U.S. government (".gov") webpage. That occurred in the announcement of

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[45] The "copyleft" provision of the GPL license enjoined a license-holder who distributed the software code to others enjoined them to make it available on the same free and open terms on which they had received it -- including such modifications as they had introduced. This use of intellectual property protection to accomplish by contract a purpose antithetical to the usual profit-seeking restrictions of the licensing terms imposed by copyright owners has been memorably characterized (by Benkler 2002) as a form of *legal jujitsu* – turning the exclusive power (conveyed by copyright ownership) against one's opponent.

[46] See the conference main webpage (http://openscience.bnl.gov), which is the first place the term "Open Science" appeared on a U.S. government website, but in no other connection than the federal status of the BNL which hosted the conference. The "Motivations" page of this site declared that: "Open Source/Open Science is a unique conference: scientists, who rely heavily on the Internet and many open source projects to advance their research, are brought together with some of the leading figures in the Open Source community [e.g., Bruce Perrens] for the first time". Coincidentally, and purely by chance, the first use of the term "open science" in my publications occurred shortly thereafter, in David (2000) -- a SIEPR Discussion Paper that drew upon material prepared for an invited presentation to the World Bank ABCDE conference held in Paris earlier that year, in 2000, the text of which was publicly distributed along with other conference papers by the Bank after a two-year delay (see David 2002).

a White House event held in June 2013, at which "Obama Administration officials honored 13 extraordinary leaders and organizations selected as 'Champions of Change' for their work using and promoting open scientific data and publications to grow our economy and improve our world."[47]

The idea of "copy-left" pioneered by the open source software movement has had wider and more profound ramifications by inspiring the beginnings of a kindred movement to develop the tailored uses of "contractually constructed commons" for purposes beyond preserving and facilitating future sharing of existing intangible and tangible research resources that can be accessed on the Internet.[48] Common-use licensing, by effecting the contractual "pooling" of specific bodies of information and data that have been protected under intellectual property law, can be used as a way to liberating particular scientific projects and entire research programs from the costly, time-consuming and sometime overwhelming impediments that collaborative research would encounter in the form of key "blocking patents"; and equally from "thickets" of patents on numerous complementary research tools when the individual legal rights to their use are separately owned by many different parties.[49]

Thus, the Neurocommons Project, a collaboration between Science Commons and the Teranode Corporation,[50] undertook to accelerate the progress of research in that field

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[47] See http://www.whitehouse.gove/blog/2013/06/21/celebrating-open-science-champions-change-white-house . Although long in coming, this public acknowledgement (at the Presidential level of the U.S. government) of the importance of institutionalized open science principles and the enhancement of capabilities for implementing them in collaborative research, was an encouraging omen regarding the institution's survival. In itself, it hardly can be taken as assuring the institution's future, or even supportive federal government efforts.

[48] On the contractual construction of "commons" for shared use of intangible (digital) scientific research resources see the important early scholarly contribution by Reichman and Uhlir (2003), as well as David and Spence (2003, 2008) on legal and organizational issues. For the extension of this approach to the case of tangible research resources, specifically the construction of "the microbial commons" and other applications, see Dedeurwaedere (2010, 2011), and National Research Council (2011). Reichman, Uhlir and Dedeurwaedere (forthcoming, 2015) formulate principles for the design of governance arrangements that could be adapted to idiosyncratic requirements of particular research communities, while permitting subsequent "federated commons" to evolve and function effectively.

[49] On the conditions for "economically efficient" patent pools, and the avoidance of the abuse of common-use licensing for anti-competitive purposes, see David (2010) and references therein.

[50] See http://neurocommons.org/page/Main Page and http://neurosicience.org. Creative Commons (*CC,* hereinafter) is a 501(c)(e) non-profit tax-exempt organization chartered in Massachusetts and currently headquartered in Mountain View, CA: http://www.creativecommons.org. It was founded in 2001 by Lawrence Lessig (then at Stanford), Hal Abelson (MIT) and Eric Eldred (at the time an independent scholar and literary agent in Boston), with the purpose of expanding the corpus of creative works that are publicly available and shared, by developing a range of alternative copyright licenses and making them freely available. In 2005, Lessig founded Science Commons (http://www.sciencecommons.org) as a semi-autonomous program of *CC* in 2005, with the parallel purpose of creating legal (and later technical) infrastructures for the open distribution and sharing of scientific information and data. [Disclosure notice;

by using licensing agreements to build an open access neuroscience information and data commons -- the contents of which are digital, online, free of charge, and freed of most copyright and licensing restrictions for use by neuroscience research projects. Further, the constructed "neuroscience patent commons" forms a base for the development of a "semantic web" that links publications, datasets and working-paper and journal and citations to their research uses. This pioneering organizational exploration of the possibilities of transforming the way that collaborative biomedical research is conducted has been followed by others, and elaborated by the still more ambitious Sage Bionetworks worldwide program for drug discovery that was launched in 2009.[51]

"Bottom up" initiatives on the part of publicly funded researchers have been creating specialized and sophisticated technical, organizational and legal infrastructures appropriate for their collaborative scientific work. But, the existence of those structures had further, external effects. They provided concrete exemplars that stimulated and rendered more feasible a variety of policy actions and regulatory measures by government science agencies, which in turn reinforced and broadened the movement to provide and protect conditions of open and timely global access to scientific data and information. Starting in the United States, such government actions eventually were taken up in varying degrees by Canada, United Kingdom, France, Germany, Switzerland, the Netherlands, Finland, Australia, and South Africa. The international percolation of these governmental policy measures was stimulated and to some extent guided by the coordination and dissemination activities that stemmed from sustained efforts within the OECD to develop a common set of "recommended principles and guidelines to promote access to publicly funded research data".[52]

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the author served as a member of Science Commons Scientific Advisory Board from 2005 until 2009 when the organization was re-absorbed into *CC*, where work on the neurocommons semantic web project continued.

[51] See http://www.sagebase.org. Sage Bionetworks, founded as a non-profit research organization in 2009, has a lineage dating back to 1994, when Stephen Friend and Lee Hartwell launched the "Seattle Project" whose purpose was "to link genetics and drug discovery, based on the assumption that pattern recognition could allow researchers to intuit cellular activity directly from data as opposed to using hypothesis-driven, narrative approaches to biology." The organization's technology platforms facilitate collaboration on data, while its governance platforms enable data sharing and reuse, run challenges to solve complex biomedical problems, as well as conducting its own computational biology research. A draft statement of six "Commons Principles" for open, contributor-driven genomic research and progressive community engagement to define behaviors and processes for those working in the Commons computational environment, and more generally "for researchers interested in cooperative, data-intensive science and patient advocacy" was approved at the *Sage Bionets* annual Congress, held in San Francisco in April 2011, and, after further revisions, was approved by the organization's Board of Directors (see http://sagebase.org/2011/06/13/principles/). Dr. Stephen Friend, who has led this organization was among the "heroes of Open Science" hailed at the White House-OSTP celebration in June 2013 (see note 46 *supra*).

[52] See OECD (2007), the eventual outcome the Working Party's years of effort to produce a consensus document.

Such "top down" policy initiatives were able to point to principles and models provided by the earlier practical successes of major international scientific collaborations in astrophysics and astronomy, as well as those in genomics. For example, the policy precedents established by the Human Genome Project's rejection of intellectual property protection of gene sequences, and its requirement that data on new sequences be released daily within the collaboration, were subsequently followed by the International Haplotide Mapping Project's introduction of a novel, special-purpose "click-wrap" license that served to thwart the patenting of genotype data with potential commercially uses and thereby secure open data-sharing.[53]

The main lessons and implications for the future vitality of open science institutions that can be drawn from the foregoing selective sketch of the experiences of the past 15 years is that research communities of this kind possess not only the technical and organizational ingenuity, but also the organizational capabilities to apply them to sustain their culture and protect their characteristically efficient collaborative modes of conducting socially valuable exploratory, fundamental research. To go on doing this, however, they must be adequately supported by external, public and charitable sources of funding, and nurtured by "top down" public policy actions that reinforce and help them reproduce the ethos of open science in successive generations of university-trained researchers.

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[53] The "Haplotide Map" is a database tool that was created to greatly reduce the cost and time of identifying blocks of sequenced DNA containing genes and genetic variations that affect health and disease. Work on the HapMap project initiated by the Human Genome Project in 2001 has been continued under the National Human Genome Research Institute (see https://www.genome.gov/10001688).

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Figure 1

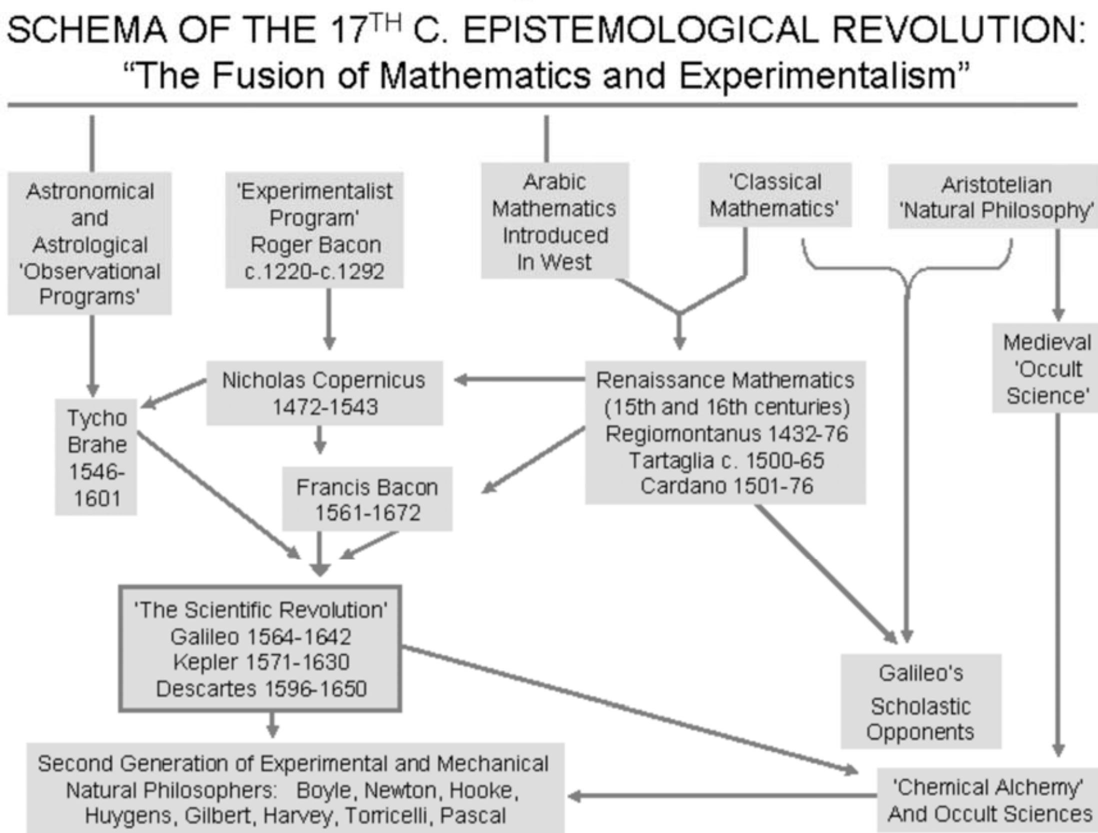
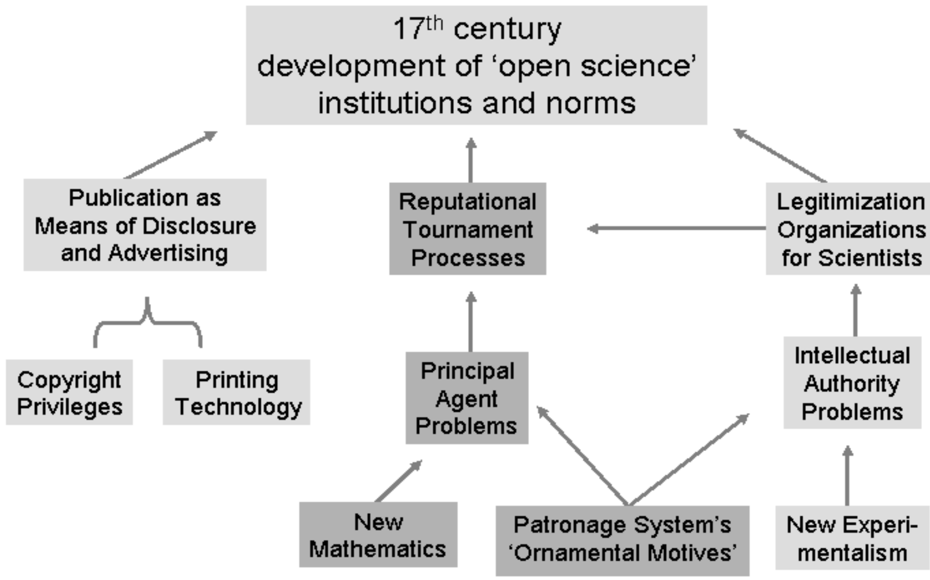


Figure 2

'Historical Origins': Structure of the Argument



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