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# Heterogeneous systems and common objects: The relation between global and national science

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## Abstract

The impact of global convergence and integration has been uneven by social sector but has been especially pronounced in networked communications and in knowledge, which is facilitated by communications. Since the advent of the Internet in the 1990s a global science system has emerged, exhibiting the classical network properties of open entry and rapid expansion and intensification. In turn this has stimulated the growth of national science systems. The paper theorises the global/national interface in science and reviews the handling of scale in recent literature, primarily in scientometrics. It also synthesises the literature's insights into global science, including factors shaping association between scientists. Global and national science are heterogeneous (national science has a normative centre while autonomous global science is regulated by collegial networks independent of states; global scientific networks grow more rapidly than national networks) but science in the two scales has achieved symbiosis. While the collaborative global scale is often where the scientific cutting edge is located, science is financed nationally. There is a large zone of common objects shared between the systems, including scientists active in both. For the most part the global/national relation in science is not well understood in the literature. Many studies are stymied by normative globalism (e.g.

the assumption that international collaboration is necessarily beneficial to quality) or methodological nationalism (e.g. arbitrary allocation of global data between nations for the purposes of comparison, which altogether removes the cross-border global system from empirical scrutiny, despite its dynamism). The paper argues for a multi-scalar approach to analysis of science, and expands on the differences, synergies and tensions between the global and national systems.

**Keywords**: Globalisation, Knowledge, Science, Research, International collaboration, National science policy, Developing countries, Scientometrics, Co-authorship, Citation

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# Introduction: Globalisation, nations and science

### 1990s globalisation: Communications and neo-liberalism

The advent of communicative globalisation in the 1990s was a fundamental change, akin to the invention and generalisation of printing in late medieval Europe, and the widespread diffusion of transport driven by processed energy in the nineteenth century. The networked world would have been a fundamental change in any era, and in any era its meanings were bound to be coloured by the particular historical context. So it was in the 1990s and after.

The proportion of the world's population connected through the Internet grew from 0.05 per cent in 1990, many in early adopting United States' (US) universities, to 6.53 per cent in 2000 and 15.67 per cent in 2005 (World Bank, 2021). The rollout of the communications network coincided with the triumph of American global policy following the dissolution of the Soviet Union in 1991, and the spread of neoliberal deregulation in trade and finance, facilitated by country adjustment to the templates of the World Trade Organisation (Rodrik, 2018). Taken together geo-politics, the high capitalist neo-liberal ascendancy, communications, financial flows, the offshoring of production, trade liberalisation, worldwide consumption and iconic brands suggested an outcome combined, singular and hegemonic: Anglo-American economic, cultural and technological globalisation seemed on the brink of remaking the world as an Americanised world order. From a critical perspective *Empire* (2020) by Michael Hardt and Antonio Negri described a networked American-centred power combining political economy, cultural practices and common ideological forms, expanding without limit across the whole global space, breaking down every barrier (p. xii-xv). In the face of the global tide many business analysts and social theorists forecast the decline or even the vanishing of the nation-state.

Orthodox business literature celebrated the weakening barriers to mobile capital, with the world made safe for business by the 'submerged state' (Mettler, 2011) of the US polity, which protected the essential freedom to trade through its ascendancy over other political powers. In this framework the decline of (non-American) nation-states was both a norm to be achieved and fact already apparent. Social theorists had other goals. They celebrated more porous political and cultural and borders and an emerging cosmopolitan super-space. They agreed with some neo-liberal analysts and many multi-national corporations that the nation-state was in trouble. In *Globalisation* (1995) Malcolm Waters acknowledged that while so far globalisation had been cultural rather than political, it looked irresistible – though he hesitated at the end of his book, stating that 'if states survive globalisation then it cannot be counted the force that it currently appears to be' (122). Arjun Appadurai (1996) was more certain: 'I have come to be convinced that the nation-state, as a complex modern political form, is on its last legs' (19). And good riddance: the nation-state system 'seems plagued by endemic disease' (20). Ulrich Beck (2005) declared that the 'national era' was passing and the 'cosmopolitan era' had begun (2). Saskia Sassen (2002) talked about the 'partial unbundling or at least weakening of the nation as a spatial unit'. The architecture of cross-border flows, in which global cities were central, 'increasingly diverges from that of the interstate system' (1). In *Globalisation and Organisation* (2006) Gili Drori, John Meyer and Hokyu Hwang saw something similar, though their focus was at a more disaggregated level than that of cities. As they saw it, the locus of activity had moved above the state, to the level of world society, where common templates 'construct the world as an integrated collectivity', and downwards below the state to the real players, the 'autonomous organisations' (19). This resonated with the global/local dual ('glolocal') that was often referenced in public commentary. Marie-Laure Djelic and Kerstin Sahlin-Andersson (2006) agreed with the Stanford institutionalists that 'world society', permeated by common 'rational, organized and universalist' institutional frames, was now the reference point. Though there was no global state, 'the alternative to state power is not anarchy and chaos' because 'the cultural and institutional web characteristic of world society can be, at least in part, a functional equivalent to a centralized, state-like global power' (14). It was not far from Hardt and Negri (2000), though the networked world imagined by Djelic and Sahlin-Andersson was more benign and the normative Anglo-American centre less obvious.

In retrospect the degree of agreement is very striking. So is the degree of error. What distinguished all of these arguments was the either/or logic of relations between the global and national scales – the assumption that 'globalisation', which David Held and colleagues (1999) defined as processes of convergence and integration on the planetary scale, necessarily meant a reduction in the role or potency of the nation. In the 1990s the possibility that both global and national structure/agency could advance simultaneously was less considered. Yet historically, the evolving nation-state had always been joined at the hip to global developments. The rise of the modern form of the state in the nineteenth century was stimulated by global convergence, comparison and competition between Britain, Prussia, France and later the United States, Japan and others (Bayly, 2006). This suggested that notwithstanding the anti-statist and 'submerged state' ideology in the politics of deregulation, the accelerated globalisation of the 1990s meant not the withering of the nation-state, but a change in its conditions of operation, and a partial transformation of its activities, while all units of the world order became more engaged and interdependent.

***Universities and science.*** Not everyone saw the state as finished or even diminished. In their overview of globalisation, with its detailed review across multiple fields, Held and colleagues (1999) carefully kept the question open. Meanwhile, in individual sectors the question of the respective roles of national and global was (as it still is) a practical issue. Universities provided one test of the 1990s arguments about decline in the role of the state. The higher education sector had been state-built across the world after World War II, and also had always been closely implicated in global communications and cross-border flows, especially in relation to research science, and models of the university (Kerr, 2001).

In higher education the 1990s launched a long wave of globalisation in student and academic mobility, research collaboration, offshore campuses, the diffusion of common systemic and institutional templates, global rankings and evolving policies on fostering cross-border passage, international collaboration in science, and global university missions. In higher education policies much emphasis was placed on the abstract imperatives of the 'global knowledge economy'. This rhetoric was misleading. While some Anglophone systems (UK, Australia and New Zealand) commercialised international education, this was not the majority approach. Across the world, the fecund globalisation in universities and science derived primarily from communicative and cultural globalisation, in association with the cheapening of travel, rather than from economic globalisation and neoliberal markets – though as with globalisation in general, for a time all of the drivers in higher education seemed to coincide (albeit on Anglo-American terms). The default position in universities everywhere was the need to respond to global changes, but one school of thought asserted the idea of ‘internationalisation’, grounded in cooperation within a multilateral order, foreign aid and cultural engagement, in opposition to the business approach to cross-border education and the advocacy of neoliberal economic globalisation (Knight and de Wit, 1995).

The 1990s in higher education were also associated with continuous processes of corporate and quasi-market reform, beginning in the neoliberal Anglo-American countries at the end of the 1980s and spreading across the world into the 2000s. These reforms, which were nuanced by country with varying mixes of changes in governance and economics, were orchestrated by national governments. In this there was no apparent reduction in the policy potency of governments, though their roles were changing. Marketisation enabled states to devolve downwards part of the responsibility for funding and outcomes downwards. They used the game settings of more competitive systems (Marginson and Considine, 2000) to determine the nature, outcomes and cost of the work less through direct administrative fiat and more through programmed self-regulation, ‘governmentality’ (Burchell et al. 1991) and ‘responsibilisation’ (Rose, 1999) in Foucault’s sense. The discourse of neoliberal globalisation became blended with discourses about university marketisation (Olsson and Peters, 2005), for example in the commercial market in international education where it was practised, and the positioning of institutional science as the platform for industrial innovation. Nevertheless, even in the case of the global student market, in which Anglo-American universities secured corporate freedom and revenue, the activity continued to be platformed and regulated nation-states. For neoliberal governments higher education was a new way to generate revenue from the export of services. Science policy also continued to be nationally driven and funded.

It was clear that when operating offshore universities had more freedom of initiative than within the territorial boundaries of the nation. Yet when they returned home the government continued to regulate them as before. It showed no sign of withering away. In higher education studies the ‘glonacal’ paper by Marginson and Rhoades (2002) responded to claims in social theory, popular discussion and higher education itself that a global/local dialectic was displacing the role of the nation-state. The paper was also grounded in observation of the multi-scalar strategies pursued by university executives. Marginson and Rhoades argued that on one hand the global scale had become more significant in higher education and research; while on the other hand, increased global integration and activity did not necessarily constitute a decline in the role of national government. Higher education was irreducibly global, national and local at the same time and agency was exercised in each scale. Scales were not mutually exclusive, and relations between scales were an open question. It was important to understand what was happening in each scale, the potential of simultaneous multiple actions in different scales, and the strategic intersections between scales. For example, when governments applied funding parcels to develop new World-Class Universities (Salmi, 2009) as science powerhouses, this combined national and local-institutional agency in fostering agency and activity in the global scale; in the process transforming local-institutional agency into also becoming global-institutional agency.

The glonacal argument also left open the possibility that spatiality in higher education and elsewhere was heterogenous – that the scales were not simply ascending structural replicas of each other but were diverse and fundamentally different in their materiality, agency and relations. Pieterse (2018, 182) critiques what he describes as ‘scale inflation’, the assumption that one scale, such as regional, national or global, can be read in the terms of another. Here the waters have been muddied by metaphorical transfers between the biological and social worlds. Studies of natural phenomena identify ‘scale invariance’, where parallel growth with self-similar patterns and regularities appear at different levels of observation. Katz and Ronda-Pupo (2019) provide the example of a plant with a flower with separate florets, each mimicking the shape of the first flower. The smaller flowers generate separate florets which do the same, and so on as the scales diminish (1046-1047). Ferns are also patterned in this manner. But as will be discussed, local, global, regional and national higher education and science are not. They are qualitatively different to each other.

Marginson and Rhoades (2002) was primarily focused on institutional higher education. They made little reference to basic science, which in most countries is largely housed in universities (Baker et al., 2019). Arguably, though, science provides a more developed instance of 'glonacal' relations than does the education function of universities, or even institutional strategy. For the most part universities are primarily nationally and locally defined: Friedman's (2018) study of elite universities in the US and UK finds that despite the stated commitment of university leaders to their global mission, 'everyday nationalism' is more fundamental in determining their actions. International student mobility constitutes a large part of the student body in some universities without substantially changing the curriculum (Marginson et al. 2010). However, science is different to higher education in this regard. Global networking in science is often primary in the formation of knowledge, as will be discussed. The national and global scales are more equally weighted in science than in education, where mission, students, curriculum and pedagogy are primarily shaped by national-local factors. Further, where global influences have the most weight in universities, for example in the normative power of global rankings and in the role of research in mediating university prestige, there global science is integral.

**Outcomes: The nation-state continues**

Two decades after the highpoint of Anglo-American globalisation it is instructive to compare the 1990s/2000s forecasts to the outcomes, in general and in higher education and science.

There has been no fundamental destabilisation of the nation-state form. The contrary is the case. Supported by a modernisation of government partly stimulated by global integration, in East Asia and parts of Southeast Asia, South Asia, Africa, the Middle East and Latin America, nation-building has proceeded at a faster pace than prior to

1990. The uplift of states has not happened everywhere. However, it has been sufficiently broad and grounded to lay to rest both the claims of world system theorists that the ‘periphery’ is trapped in permanent dependency in a Euro-American world and cannot lift itself (Wallerstein, 1974; Smith, 1979), and the above globalist assumptions that modernisation is secured by global networks, markets or ‘world society’ operating independently of states. Key events, including the conflictual geopolitics after 9/11 in 2001, the stabilisation of economies after the 2008-2010 shock, and the diverse governance of the 2020-2021 pandemic in different parts of the world, have seen the reassertion of the central role of nation-states in human affairs. This does not mean that globalisation has unilaterally reversed. In some respects, the contrary is the case. The outcome has been mixed and complex, varying by social sector, demonstrating that spatial transformations are not necessarily universalising. The simultaneity of sectoral tendencies in the 1990s, like the coupling of globalisation with Anglo-American neo-liberalism which for a time seemed to provide a unifying framework for the emerging spatiality, was episodic not permanent.

First, the communicative network has continued to expand outwards: by 2018, 50.76 per cent of the world’s population accessed the Internet (World Bank, 2021). Second, and associated with this, the process of cultural convergence has continued, though this does not mean that a single world culture has formed. In fact, third, Anglo-American globalisation in political economy and political culture has given way to a more multi-polar order. It is now clear that there are several civilisational blocs in which agents see the world in distinctive ways. Each bloc is too large and robust to be reduced wholly to domination by another: the United States, still the strongest, Western Europe, China, Japan and Russia; and emerging India, Brazil and Latin America, and perhaps Indonesia. With the rise of East Asia and nation-building and economic development in Africa and Latin America, ‘East-South’ relations are now as important as ‘North-South’ relations, and in volume terms the China-India nexus in trade will become the world’s largest (Pieterse, 2018). This combination of global convergence and difference makes a new kind of world. ‘Due to the onset of global interdependence’, the present period is ‘the first time that such a diverse set of orders intensely and continuously interact with each other' (Macaes, 2018, 2).

Fourth, consistent with partial decline in the neo-imperial Anglo-American hegemony, and in contrast with the continuing spread of global communications, there has been a slowing and possibly a reversal in the 1990s formation of world economic markets. In the decade after the 2008 recession multinational profits declined by 25 per cent, partly because of competition from modernised local firms; the share of exports accounted for by cross-border supply chains stopped growing, and foreign direct investment declined sharply (The Economist, 2017). There were few efficiency gains from the further lowering of trade barriers, the number of losers generated by trade liberalisation, like American workers displaced by offshoring, grew (Rodrick, 2017, 5-7, 27), and after 2015, in association with fractious geo-politics between the major blocs, competitive protectionism returned.

***Universities and science***. Fifth, however, the global trajectory of higher education, and more so that of science, have had globalisation trajectory more closely resembling that of global communications than that of global economics. When economic globalisation faltered after 2008 the globalisation of higher education and science continued unabated.

There have been low barriers to the mobility of ideas and data, and, prior to the pandemic, to academic travel. Opportunities to work and study in other countries are uneven by country and subject to periodic tensions. For example, the US has been notable in providing a relatively open door to foreign scientists, and as the largest science system in the wealthiest economy has been a magnet for talent, but between 2017 and 2021 the nation imposed bans affecting travel from some middle Eastern countries (Chinchilla-Rodriguez et al. 2018a) and from 2018 began to 'decouple' its scientific connections with China (Sharma, 2020), inhibiting the mobility of students and researchers (Lee and Haupt, 2020). Nevertheless, until the 2020 onslaught of the Covid-19 pandemic, global student mobility rose each year, from 1.95 million in 1998 to 5.57 million in 2018, an annual increase of 5.39 per cent (UNESCO, 2021), much faster than the annual growth of 3.58 per cent in combined world GDP PPP (World Bank, 2021). Further, scientists can collaborate without physically working alongside each other. Between 2000 and 2018 the volume of papers in Scopus rose by 4.94 per annum and the proportion of papers with authors from two or more countries rose from 13.6 to 22.5 per cent (NSB, 2020).

This decoupling of sector trajectories, the continuing globalisation of science and higher education while the economy became more nation-bound, is significant for theory. First, it shows that the dynamics of global integration and convergence in universities and science are more cultural than economic, and lays to rest the lingering idea that the economy drives everything else. Second, it also indicates the importance of national political economy, which houses and resources scientific institutions and their personnel, in sustaining global scientific activity that ranges beyond the writ of the nation-state itself. The economy is not the engine of science but it is a necessary (though not sufficient) provider of cash flows that are the fuel of science. This conjunction between (a) cultural and inter-agential globality and (b) national political economic conditions has become central in the evolution of science.

The networked global system of science, grounded in the common pool of publications, synchronous global communications and data exchange, and collaboration between scientists, which did not really exist prior to 1990, has displayed exceptional dynamism. Yet no withdrawal of the nation-state is evident, from either science or the universities housing science, and the aggregated national investment in science has grown as a proportion of GDP (OECD, 2021). ‘The growth of the global network in science does not mean we are witnessing the death of the nation-state or even a reduction in its influence in scientific investments’, as Leydesdorff and Wagner remark (2008, 324). The proportion of total papers that are co-authored by scientists from the same nation and in different institutions have grown almost as much as papers with international co-authors (NSB, 2020). If co-authorship is a guide to scientific networking and activity, these have expanded simultaneously in both the global scale and the national scale. Further, as will be argued in this paper, the two tendencies supply positive conditions for each other. The worldwide network of scientists has emerged alongside national science systems, both separate from them and overlapping with them, in symbiosis and in tension. Science is important. These facts, which negate the idea of globalisation as being zero-sum with nation-states, suggest the need to look more closely at relations between national and global science.

***Contents of this paper.*** There is no clarity in the literature about relations between global and national science, and less explicit discussion of this strategically significant topic than might be expected. This paper investigates those global-national relations by synthesising work on spatiality and scale in science and theorising the relations between global and national science systems. Research at the base of this paper included a review of approximately 200 papers in science policy and scientometrics focused on aspects of global science. This included a comprehensive reading of all papers published between 2018-2020 in the principal journals, and significant earlier works selected on the basis of bibliographical trails; and also analysis of secondary data (NSB, 2020; Leiden University, 2020) sourced in the two main bibliometric collections (WoS, 2020; Elsevier, 2020). The present paper is not written in scientometrics but from a social theory perspective and in higher education studies, which draws on various fields in social science (Callender et al., 2020).

The next section of the paper establishes the material terrain in outline. It defines and distinguishes global science and national science and compares tendencies in the evolution of co-authorship in science on one hand across borders (global networking) and on the other hand within nations (national networking). The section that follows moves to theory and reviews the concept of scale and perspectives on scale in science. With these elements in mind, the paper then works through an extended review of the literature. First is a section that overviews the handling of scale, including multiple scales, in scientometric papers. Second, is a critical review of totalising concepts of scale – some grounded in methodological globalism, most grounded in methodological nationalism – that are used in scientometric studies. Third, there is discussion of papers that have moved beyond totalising frameworks and provide substantial insights into spatiality and scale in global science, including the factors affecting collaboration in the global system, and antinomies of locality and distance and their effects in collaboration and production. The concluding section summarises the main points of the paper and expands on the junctions where the global science system meets the national science systems, and the synergies and tensions, and reflects on the implications of the paper for theorisation of science and globalisation.

## Global and national science

Table 1 distinguishes the global and national science systems. (Note that some of the claims made in the table are addressed in more detail later in the paper). By 'system' is simply meant a set of elements that form an interactive whole within defined boundaries. By 'global' is meant activities and relations that constitute a planetary ontology, that is the boundary, and tend to the evolution of the world on an integrated basis (Marginson, 2011; Conrad, 2016). 'National' is defined by the territorial borders of particular nation-states.

**Demarcating the two systems**

Table 1 and Figure 1 suggest the separation and co-existence of global and national science. The global science network is a distinctive system in its own right. Leydesdorff and Wagner (2008) find that 'international collaboration in science can be considered as a communications network that is different from national systems and has its own internal dynamics' (p. 317). For them 'global science' is constituted solely by cross-border authors and separated from scientists engaged in nation-only or sole authored publication. This contrasts with the present paper, where the 'global system' includes not only international co-authors but all scientists in the global literature, and citation and co-authorship linkages, as well as knowledge developed in that system, which is collective and communicative in form. Thus defined, the global system partly overlaps with national science. In other respects, the two papers are in agreement. Leydesdorff and Wagner emphasise the dynamic growth of global science, and the autonomy and openness of the network. 'The global network has a culture, pathways, and norms of communication specific to its structure, and diverging from national, regional, or disciplinary norms' (Wagner et al., 2017, 1646). Importantly, there is no normative centre.

**Table 1. Global science system and national science system in basic science**

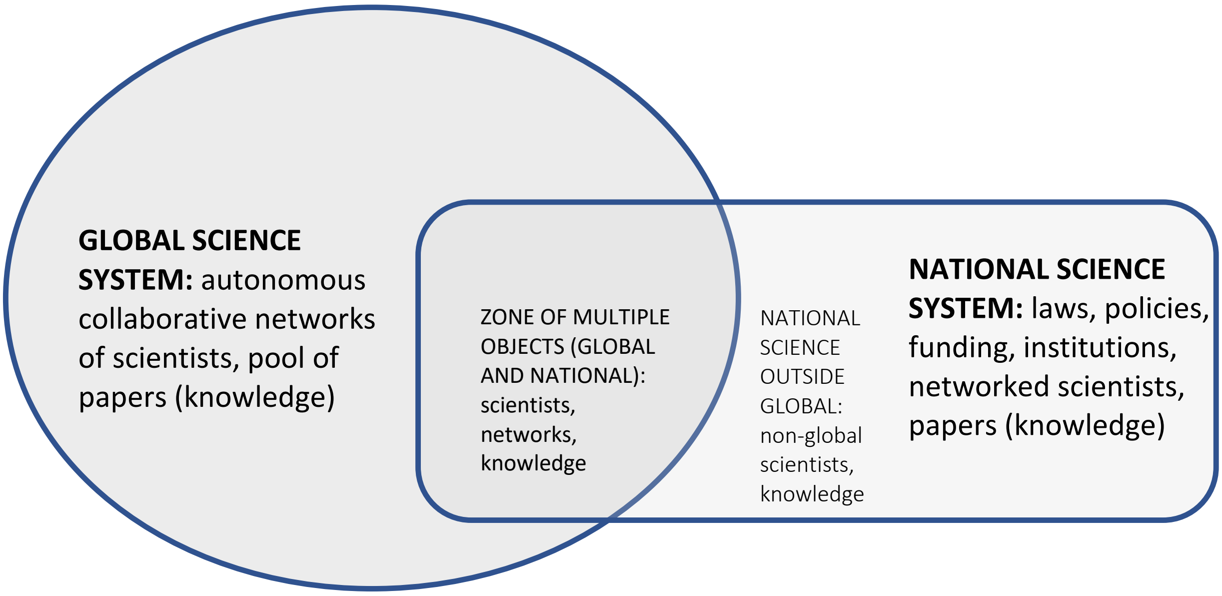
| | **Global science system** | **National science system** |
|---|---|---|
| Main functions | Production and circulation of new knowledge via networked activity | Legal, political, financial, institutional conditions. Some knowledge, applications |
| Boundary | World society | Nation-state |
| Normative centre | No normative centre | Nation-state |
| Knowledge contents | Papers published in journals admitted by WoS and Scopus | Most contents of global journals plus further nationally circulated materials |
| Social relational contents | Collegial groups of scientists operating in networks | Government agencies, research organisations, networked scientists |
| Collective loyalty | Diffuse: disciplinary community as persons and as shared knowledge | Concentrated: national and institutional authorities |
| Incentives | Cognitive discovery and accumulation, individual status | Applications of science; revenues; individual cognitive, career and status |
| Regulation | Local self-regulation on the basis of global collegial scientific norms | National law, official regulation, policy, financing systems, cultural norms |
| Resourcing | Mostly from national systems. Limited international sources | Primarily national government. Other public and private sources |
| How this system affects the other system | Knowledge potential of global science stimulates state funding | National resources, institutions and personnel underpin global science |

Source: Author

> Patterns in international collaboration in science can be considered as network effects, since there is no political institutions mediating relationships at that level [aside from the European Commission] … The emergent pattern of the global system is not created as the result of the actions or plans of a single entity or actor in the system (Leydesdorff and Wagner, 2008, 317 and 323).
>
> The macro-behaviour of a network is not the result of the micro-features or motivations of the agents. The formation and persistence of structure becomes

the equivalent of an organization. The network provides attractive, resource-based opportunity to participants. The international level offers benefits that outweigh the transaction costs of working with people who are geographically remote (Wagner et al., 2015, 8)

**Figure 1. Global and national science systems and the zone of multiple objects**




Source: Author

Global science is an emergent self-forming organisation created through the structures, processes and contents of scientific collaboration, rather than through conscious design: a singular result without a singular cause. It is a self-regulating system grounded in bottom-up cooperation among scientists with common beliefs and practices. This is confirmed by many other scholars (Georghiou, 1998, 611; Schott, 1998; Melin, 1999; Chen et al., 2019; Barrios et al., 2019; others). The notion of science as 'intrinsically cosmopolitan' as posited by Robert Merton was widely propagated in the post-World War II period, especially by leading scientists themselves (Mallard and Paradeise, 2009, 2). Governments and public opinion were at least partly persuaded that science was necessarily disinterested, intellectually objective, and committed to universal truths and rational procedures. Central to this was the practice of autonomy from 'political and particularistic forces, like those of nation states' (3). The autonomy of global science should not be overstated. Multiple investments and subjectivities – disciplinary community, national career, local institution – are the norm in science. Scientists rarely operate on the basis of a complete Mertonian autonomy from the state (32). Further, scientific autonomy varies on the basis of rules, funding, stage of career and the position of the scientific institution within the field of institutions (4). However, the point is that the epistemic spaces that scientists inhabit, which are intrinsically cross-border in character, provide them with at least some space to determine the combination and balance of their commitments. Scope for reflexive self-regulation is specific to the cognitive character of the work, within global science that is based in 'sociability rather than sovereignty' (King, 2011, 359). However, in all fields of knowledge the shared discipline requires at least some Mertonian adherence to norms that range beyond particularistic identity. It can be argued that scientific community is a form of global civil society. This does not mean it is a flat universe in which every individual unit is equivalent. Like most civil societies, global science is bordered and is socially hierarchical within. It is also hegemonic in operation at world level. Scientific publishing and professional norms are led by Anglo-American research universities, largely exclude science from outside the English-language conversations, routinely devalue work that does not embody Euro-American cultural norms, and tend all else equal to reproduce the dominance of the established strong institutions (Marginson and Xu, 2021).

The difference between national and global science is above all grounded in the autonomy of the global system and the freedoms this brings to its practitioners. 'National systems have policies and institutions that mediate scientific communication, while at the global level the network exists primarily as a self-organizing system' (Leydesdorff and Wagner, 2008, 317). Unlike the global system, each national science system is normatively centred by its nation state. Governments expect science to contribute to the goals of the state, including prosperity and security. Nation-states are the main agents that structure and resource science, including global science networks. They provide the legal, political/policy and financial conditions and nurture the institutions where most basic science is developed, universities and public laboratories, academies and institutes. Hence national systems incorporate elements other than science, including politics, economic and financing, governance and law, opening out into the organisation of cities, states and societies. Hennemann and colleagues (2012) note that ‘important forces act on the national scale’ including funding bodies, competition between universities, and the labour markets for science; while on the sub-national scale companies influence scientific activities and research organisations ‘cluster in urban agglomerations’ (217-8). National systems, often disproportionately patterned by large research grants held in a small number organisations, are affected by ‘socio-cultural features such as language and institutions (e.g. common ethics, regulatory frameworks, legal ground or fiscal idiosyncrasies)’ (223). Of these elements that distinguish national science systems, one that is open to ready calculation and comparison is the financing of science, which is factored into many studies (Leydesdorff and Wagner, 2008; King, 2011; Muriithi et al., 2017; Chinchilla-Rodriguez et al., 2018b).

Yet this complex of national structures and agents creates the possibility of the global science that differs from it, and to which it is joined in mutual stimulus and facilitation. ‘The sciences develop internationally, but the funding is mainly national’ (Bornmann et al., 2018, 931). Global science in turn provides momentum for the accelerated development of national science, by constituting a common pool of knowledge from which technological innovations are sourced. Nations need to access that emerging global science. Despite the fact that not all the science discoveries directly benefit the economy of the nation in which they occur, states continually improve scientific infrastructure and invest in projects. Here capacity is an end in itself. As *The Economist* put it, in making the case for increased state spending on R&D, including basic science: ‘As for the difficulty of capturing the benefits of national R&D spending in a global world, making use of cutting-edge technologies developed elsewhere is not possible without a lot of very highly trained locals, and such cadres are hard to produce and maintain without R&D spending’ (*The Economist*, 2021).

The two kinds of science system, global and national, closely co-exist and overlap. The relation is not uniform worldwide. At times the alignment is close. In Singapore, where the national institutions are intensively networked into and benchmarked with the global system, more than two thirds of all published papers involve international collaboration and there is scarcely a separated national conversation, corresponding to the fact that the island-state has no geographic or economic hinterland separate from its central position in global trade, so that without the global scale it does not exist. Another kind of example is the UK, where national science is nearly as globally engaged as is Singapore's – most UK papers once published immediately enter the global literature, though the UK science system differs from that of Singapore in that UK science is primarily self-referential, and partly neo-imperial in its perception of the rest of the world, rather than globally defined from outside itself (Wagner, et al., 2015). There is more than one way to be global.

Yet despite these cases global and national science are different in kind. Rather than being part of a unitary set, or even a dialectic of opposites eventually resolved as a singular unity, they are at the same time combined, heterogeneous and partly separated. They share certain objects (e.g. internationally collaborative research units that are based in a national university have functions in both global science and the national science system) while they are wholly separated in others (e.g. papers in national languages other than English rarely enter the global pool). The objects that are shared between national and global science systems include people; that is, most of the scientists themselves. Many scientists wear two different hats and have two sets of loyalties, to the cross-border discipline-based network and to their national and institutional authorities (Adams, 2013). While this multiplicity confirms the possibility of effective global-national intersections in science it also suggests that global-national synergy is not always-already automatic. It cannot be taken for granted.

**Global and national growth are different**

The global and national science systems are heterogeneous, but they share an important element. Both are sustained, though to an extent that varies, by networked relations. Networks are one structural element within the larger social relational picture. At the same time, every network has autonomous dynamics as a network.

***Growth and spread of science.*** The dynamism of global science is captured in the secondary data compilations derived from WoS and Scopus (e.g. NSB, 2020; Leiden University, 2021; Marginson, 2020). The number of journal papers and other publications in Scopus rose from 972,746 in 1996 to 2,553,959 only one generation later in 2018. Between 2000 and 2018 growth in papers was 4.94 per cent per year (NSB, 2020, Table S5A-2), while world GDP grew by 3.52 per cent per year (World Bank, 2021). In all large science countries, the number of papers associated with national citizen-scientists grew significantly, except in Japan. There was especially rapid growth in China (Marginson, 2021a). There was also a notable diversification in the group of active science countries. In the thirty years after 1987 the number of countries that contributed to 90 per cent of bibliometric output rose from 20 to 32 (Grossetti, 2013, 2225; NSB, 2020, Table S5A-2). In 2018 there were 26 larger national science systems where papers increased faster than 4.94 per cent a year ('larger' means that scientists authored at least 5,000 papers in 2018). In 12 of those 26 countries, national per capita income was below the world average of USD $16,635 in Purchasing Power Parity (PPP) terms. They included India, Indonesia, Brazil, Nigeria, Pakistan, Iran, South Africa, and China where income was just below the mean (NSB, 2020, Table S5A-2; World Bank, 2021).

The spread of networked relations is apparent in the bibliometric data. The proportion of papers co-authored outside one research organisation grew, from 47.4 per cent in 1996 to 77.5 per cent in 2018, indicating the expansion of active collaborative networks. Within the pool of global science outputs circumscribed by the bibliometric collections, both national and international collaborations increased as a proportion of papers. The national collaboration share rose from 35.1 in 2000 to 44. 4 per cent in 2018 and the international share from 12.4 in 2000 to 22.5 per cent in 2018 (NSB, 2020, S5A-32). The growth of national co-authorship within global science serves as a proxy for the building of the national science system, though it is an imperfect proxy, as that part of national scientific work not included in the global pool remains hidden. The international co-authorship proportion of 22.5 per cent in Scopus papers in 2018 compares with just 1.9 per cent of articles indexed in Web of Science in 1970 (Olechnicka et al. 2019, 78). There has been a marked increase in the proportion of papers that were internationally co-authored in the case of authors from 37 of largest 48 science countries (Olechnicka et al. 2019, 80-83), and in the last decade the internationally co-authored papers as a proportion of all papers rose markedly in nearly all leading science universities (Leiden University, 2020). There was also a marked increase in the international share of citations of nationally-authored publications in most countries, further indicating the globalisation of knowledge (NSB, 2018, Table A5-42).

As is discussed in more detail below under the heading 'Scale as materiality: The global system', in the global setting, networked social relations embody specific dynamics of structure/agency. The global science network, grounded in the autonomous links between scientists and for the most part evolving as they see fit, continually expands outwards towards every possible node while links ('edges') between existing nodes become more intensive over time (Castells, 2000; 2001; 2009). Science is characterized by open and rapid linking, expansion and diffusion while there are also growing concentrations of activity, resources and authority within it. In Castells's (2001) words 'metropolitan concentration and global networking … proceed simultaneously' (225). The 'metropolitan concentration' of network power has a dual character. On one hand concentrated relations within the network are the cause and effect of networked activity itself; while on the other hand, those concentrations are shaped, sustained and reproduced in an ongoing way by national governments and institutions such as universities. The 'metropolitan concentrations' constitute a key junction between national and global science, and the structuring power of the nation at this junction qualifies the idea of autonomous global science. For example, research collaboration across borders is often encouraged by governments and strongly incentivised within European research programmes. However, national action is not the only determinant of cooperation between scientists themselves and it may not even be a primary determinant. Rather, it funds those scientists, affects the balance of activity between activity in the different fields of science, perhaps may stimulate the rate of the work if its performance-oriented systems have purchase. The largest role for the nation, and the university, is at the point when the infrastructure of science is created. Once the intrinsic capacity is established, barring contrary national blockages the growth dynamic tends to play out in global science – though the national factor, in relation to rules and resources, may condition the speed at which edges develop and networking accumulates.

***Limits to national networking.*** The striking development of the era of communicative globalisation, the single fact that modifies the conventional picture of science as a multilateral contest between national innovation systems, is that nationally funded and located science is 'increasingly embedded within the global network' (Graf and Kalthaus, 2018, 5), and mostly without blockages by governments and universities. A quantitative measure is impossible, but it is likely that the material weight in human affairs of the autonomous global community of science is continually expanding, and all else equal its scope for self-regulation independent of national governments is also growing (though not in an even or identical manner everywhere). This also means that in Figure 1, it is likely that the zone of multiple objects tends to expand over time as a proportion of national science (though this proportion undoubtedly varies on the basis of language of use, national science policy and other factors). Rapid global system development is repeatedly discussed in scientometric studies (e.g. Wagner and Leydesdorff 2005, 320; Wagner et al., 2015, 6; Wagner et al., 2017, 1637-1640, indicating successive increases in the rate of international collaboration). The global dynamic is the pure materiality of autonomous networked science at work. Significantly, in most countries global networking is expanding more quickly than nationally co-authored papers and solo work, as indicated by the continuous growth in the proportion of all science papers that are internationally co-authored. However, the relationship between global and national network is not uniform in all times and places.

National networking, indicated by nation-only co-authorships, also expands most of the time but not always and not at the same rate as global networking, especially in mature science systems. Why is this? Is it always the case? How might it be theorised? The following account seems consistent with the data. National science networks are different to global networks in that their long-term endogenous trajectory does not solely follow a Castellian expansionary network logic. There are evident limits not present in the global system trajectory. Networked national relations in science are both enabled and constrained by non-network social phenomena, including global geo-politics and national policy, regulation, funding and institutional arrangements. While the national-level phenomena also condition global network development, a slowing of national network development in one country has limited impact on the global pattern. First, factors in one nation do not have sufficient causal weight to stymie overall global dynamics; and second, when national system building slows the networked dynamics of global growth, which are largely extrinsic to the national system, continue. At this point, in most national systems there seems to be a shift, from the positive sum relations between the growth of national and global networks, both expanding quickly, to an expansion of collaboration that is predominantly global.

This pattern varies between countries, according to both differences in their national policies (which may reflect differences in political cultures) and differences in the point they have reached on their own trajectory of national system development. There is more than one possible development trajectory, but the passage of the trajectory is significant, as well as its character. Emerging national science systems, fostered by nation-states, typically demonstrate accelerated growth in total papers. This rapid early growth is furthered not solely by the expansionary logic of the science network but also by government policies, infrastructure, funding and targets. All emerging systems grow their international collaborations as part of the capacity building process, but unless they are relatively small, with few prospective national partners, and for this reason alone largely dependent on international collaboration, they also manifest accelerated growth of nationally co-authored papers. Later, at a policy point that varies country-by-country, national systemic collaboration ceases to expand with the outward dynamic of a network. As nation-only network density increases, the natural expansionary potential of national systems, within the container, approaches a limit. This limit is set both by the structure of the national network and by national policy and financing. On one hand, national borders are shorter than global borders: there is not the same scope for grass-roots growth of new nodes and additional edges as in the global science system. On the other hand, national governments reach a political-cultural limit. The duration of accelerated nation-building in science is not fixed by a social law, it is determined by each government, but once a mature national system is reached, all else being equal the drive to build additional national capacity tends to weaken. Further, it becomes more difficult to manage the politics of funding expanded capacity. There is a trade-off between established institutional bases, which have influence, and the creation of new capacity. Funding in a mature system tends to be mostly focused on existing science, such as concentrations in leading universities, less arbitrary and controversial than creating new winners. ‘Direct R&D subsidies … only seem to encourage collaboration with already well-embedded actors’ (Graf and Kalthaus, 2018, p. 2, p. 11).

In sum, it can be theorised that as scientific activity grows in a specified nation, over time nation-only co-authorship eventually plateaus. The timing and extent of this change is determined partly by the extent to which collaboration is outwardly versus inwardly focused. Up to the point that nation-only networking ceases to expand like a Castellian network the relation between national and international collaboration is positive sum. After that point a zero-sum element becomes apparent. Only global collaborations keep growing in network fashion, and the quantitative expansion of networked activity becomes located primarily in the global domain. What is the evidence for this theorisation of global and national in science? Regardless of the ambiguity (national science is partly coincident with global science and partly separated from it), the theorised trajectory of boom/plateau in national networking is confirmed in both literature and observation.

First, the literature. ‘For the scientifically advanced nations, the internationally coauthored articles account for almost all the growth’, state Wagner et al. (2015, p. 7). In a study of 1981-2012 papers in WoS, Adams exaggerates only slightly:

> Over more than three decades, domestic output – papers that list only authors from the home country – has flatlined in the United States and in Western European countries. The rise in total annual output for each country is due to international collaboration. The percentage of papers that are entirely ‘home grown’ is falling. In emerging countries, by contrast, domestic output is rapidly expanding (Adams, 2013, p. 558).

Second, the data. The pattern of boom/plateau in national network building is apparent when comparative data are examined, as summarized in Table 2 and Figure 2.

***Data based comparison of global and national networking.*** Data on nationally and internationally co-authored papers allow direct if partial comparisons of the two different system trajectories, global and national (Frenken, 2002; Adams, 2013). The comparison appears to confirm the theorisation that global growth is more faithful to a Castellian network logic. This is clearer when examining the data for nations at different points in the development of science. Table 2 and Figure 2 track the growth of each form of co-authorship between 2006 and 2018, in 42 leading science countries by volume of papers. Because of the gaps in coverage (not all national science is included in data on co-authorships in the global literature) and the overlap between national system and global system (part of the global literature is national co-authorship), these data do not provide a conclusive sorting between the global and national science systems.

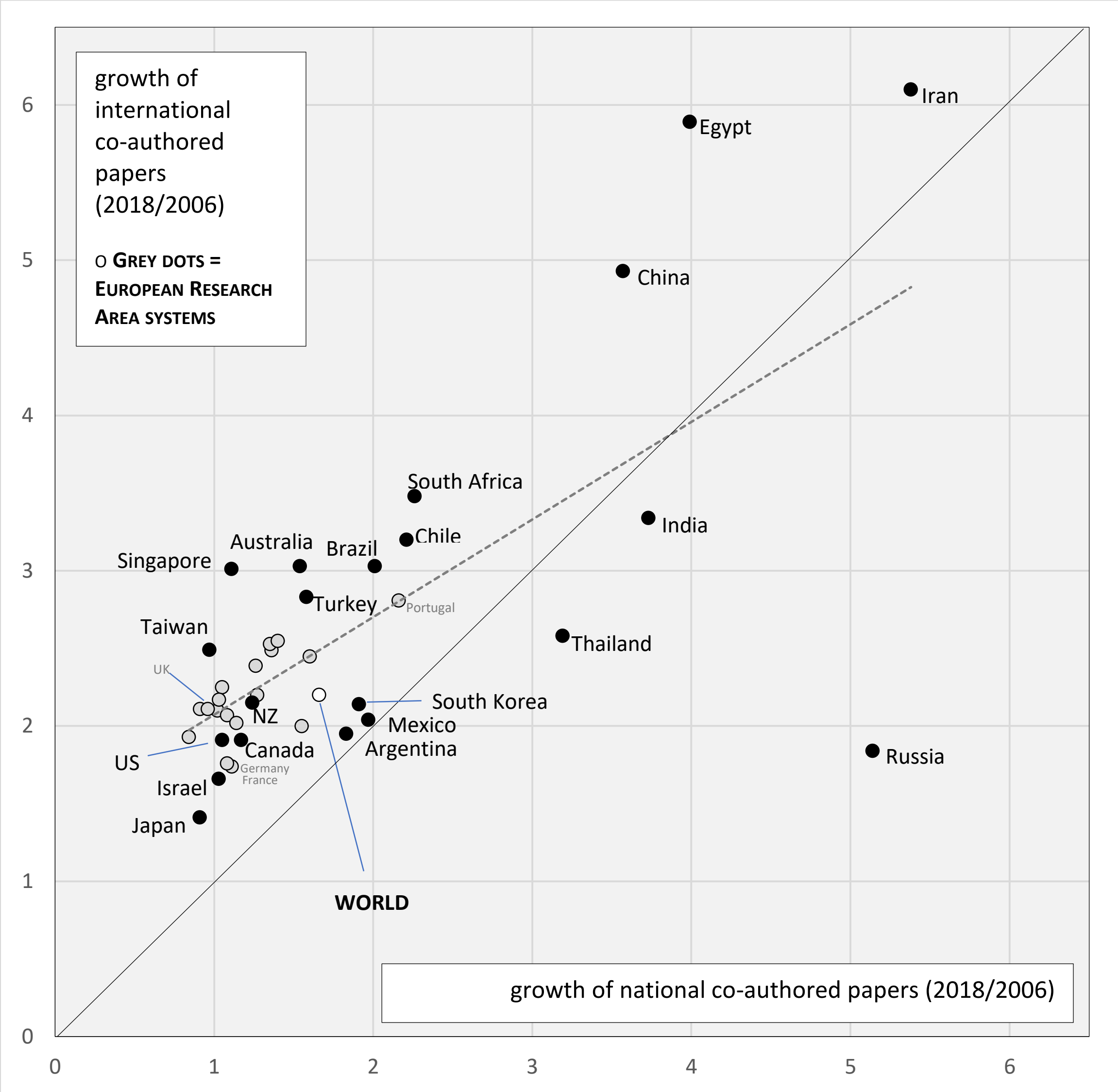
**Table 2. Growth of international co-authored papers compared to growth of nation-only co-authored papers, world and 42 research countries: 2018 compared to 2006 (2006 = 1.00)**

| System | multiplier all papers 2018/2006 | internationally co-authored papers 2006 | internationally co-authored papers 2018 | multiplier international 2018/2006 | nationally co-authored papers 2006 | nationally co-authored papers 2018 | multiplier national 2018/2006 |
|---|---|---|---|---|---|---|---|
| National systems with rapid shift to internationally co-authored papers, compared to national (systems above the broken line in Figure 2) | | | | | | | |
| Malaysia | 7.28 | 1,418 | 11,954 | 8.43 | 1,322 | 10,257 | 7.76 |
| Iran | 4.87 | 2,177 | 13,277 | 6.10 | 4,753 | 25,548 | 5.38 |
| Pakistan | 5.64 | 928 | 9,810 | 10.57 | 1,051 | 5,363 | 5.10 |
| Egypt | 3.92 | 1,727 | 10,176 | 5.89 | 1,482 | 5,918 | 3.99 |
| China | 2.87 | 25,753 | 126,868 | 4.93 | 78,749 | 280,881 | 3.57 |
| Saudi Arabia | 8.58 | 900 | 16,037 | 17.82 | 636 | 2,102 | 3.31 |
| South Africa | 2.65 | 3,218 | 11,188 | 3.48 | 1,693 | 3,828 | 2.26 |
| Chile | 2.65 | 2,534 | 8,097 | 3.20 | 1,252 | 2,761 | 2.21 |
| Portugal | 2.27 | 4,467 | 12,534 | 2.81 | 2,874 | 6,200 | 2.16 |
| Brazil | 2.23 | 8,116 | 24,610 | 3.03 | 16,811 | 33,783 | 2.01 |
| Ireland | 1.82 | 3,286 | 8,050 | 2.45 | 1,427 | 2,289 | 1.60 |
| Turkey | 1.82 | 3,426 | 9,698 | 2.83 | 11,500 | 18,158 | 1.58 |
| Australia | 1.97 | 16,709 | 50,584 | 3.03 | 13,404 | 20,628 | 1.54 |
| Norway | 1.96 | 4,967 | 12,687 | 2.55 | 2,896 | 4,051 | 1.40 |
| Czechia | 1.96 | 4,202 | 10,449 | 2.49 | 3,741 | 5,100 | 1.36 |
| Denmark | 1.95 | 6,578 | 16,670 | 2.53 | 3,391 | 4,577 | 1.35 |
| Spain | 1.62 | 17,638 | 42,137 | 2.39 | 17,546 | 22,042 | 1.26 |
| Singapore | 1.85 | 4,387 | 13,216 | 3.01 | 2,813 | 3,131 | 1.11 |
| Austria | 1.69 | 6,762 | 15,183 | 2.25 | 3,289 | 3,454 | 1.05 |
| Sweden | 1.58 | 11,377 | 24,740 | 2.17 | 6,390 | 6,604 | 1.03 |
| Belgium | 1.54 | 9,825 | 20,667 | 2.10 | 4,718 | 4,812 | 1.02 |
| Taiwan | 1.19 | 4,629 | 11,542 | 2.49 | 14,348 | 13,852 | 0.97 |
| UK | 1.39 | 47,409 | 99,924 | 2.11 | 30,886 | 29,683 | 0.96 |
| Finland | 1.43 | 5,360 | 11,323 | 2.11 | 3,826 | 3,497 | 0.91 |
| National systems with slow or no shift to internationally co-authored papers, compared to national (systems below the broken line in Figure 2) | | | | | | | |
| Russia | 2.58 | 11,708 | 21,530 | 1.84 | 6,569 | 33,789 | 5.14 |
| India | 3.49 | 7,991 | 26,684 | 3.34 | 15,837 | 59,023 | 3.73 |
| Thailand | 2.85 | 2,512 | 6,486 | 2.58 | 1,812 | 5,787 | 3.19 |
| Mexico | 1.81 | 4,688 | 9,583 | 2.04 | 4,214 | 8,282 | 1.97 |
| South Korea | 1.85 | 10,493 | 22,422 | 2.14 | 18,224 | 34,839 | 1.91 |
| Argentina | 1.68 | 3,080 | 6,004 | 1.95 | 2,311 | 4,231 | 1.83 |
| Poland | 1.70 | 7,480 | 14,950 | 2.00 | 8,840 | 13,689 | 1.55 |
| Italy | 1.59 | 22,793 | 50,243 | 2.20 | 23,863 | 30,410 | 1.27 |
| New Zealand | 1.67 | 3,833 | 8,258 | 2.15 | 1,956 | 2,434 | 1.24 |
| Canada | 1.42 | 26,787 | 51,287 | 1.91 | 18,808 | 22,001 | 1.17 |
| Switzer-land | 1.61 | 14,618 | 29,476 | 2.02 | 4,748 | 5,424 | 1.14 |
| France | 1.27 | 34,982 | 60,916 | 1.74 | 24,207 | 26,865 | 1.11 |
| Germany | 1.38 | 46,596 | 82,089 | 1.76 | 33,488 | 36,010 | 1.08 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Nether-lands | 1.51 | 16,280 | 33,713 | 2.07 | 10,499 | 11,341 | 1.08 |
| USA | 1.22 | 112,950 | 215,388 | 1.91 | 192,916 | 201,706 | 1.05 |
| Israel | 1.28 | 5,886 | 9,790 | 1.66 | 4,426 | 4,540 | 1.03 |
| Japan | 0.95 | 25,488 | 36,050 | 1.41 | 58,091 | 52,805 | 0.91 |
| Greece | 1.25 | 4,675 | 9,029 | 1.93 | 4,625 | 3,871 | 0.84 |
| WORLD | 1.62 | 262,099 | 575,857 | 2.20 | 684,143 | 1,134,859 | 1.66 |

Source: Author, using data from NSB, 2020, Table S5A-32. First group of systems are above the broken line in Figure 2.

**Figure 2. Growth of international co-authored papers compared to growth of nation-only co-authored papers, world and major research countries: 2018 compared to 2006 (2006 = 1.00)**




Nation-only collaborative papers include author(s) from more than one institution in one nation. Grey dots are countries engaged in European Research Area programmes in 2018.

Data include 42 leading research countries selected from Scopus data by US National Science Board. Dotted line is line of best fit for the 42 cases plus the world (growth multiplier 2006-2018 of 2.2 for international co-authorship and 1.7 for national co-authorship). National systems above the dotted line exhibit relatively high growth on international collaboration compared to domestic collaboration; countries below the line exhibit relatively high growth in building national collaboration compared to international. For ease of presentation the chart excludes outliers Saudi Arabia (growth multiplier 17.8 for international /3.3 for domestic), Pakistan (10.6/5.1) and Malaysia (8.4/7.8).

NZ = New Zealand. WORLD refers to all science countries and not just this group of 42 leading countries. Source: Author, using data from NSB, 2020, Table S5A-32.

To repeat, nationally co-authored papers in the global literature are a partial proxy only for networked national science. Nevertheless, these data identify the particular national systems in which there has been robust growth of nation-only collaboration, suggesting accelerated national capacity building in emerging systems. It is notable that no long-established science systems have relatively high rates of growth of nation-only co-authorships. Table 2 and Figure 2 also identify systems where growth of international co-authorship has been very pronounced, which can happen in either emerging systems or established systems. By mapping the two axes against each other Figure 2 identifies the nation-by-nation relation between the growth trajectories of global and national collaboration. Figure 2 shows which nations are moving faster than most others in one direction or the other – for example, the graph distinguishes emerging countries that especially use international collaboration as their way forward, from those emerging countries equally or more committed to national network building. (In these data single authors with more than one institutional affiliation are recorded as a collaboration, with varying effects in the data, depending on the country).

Between 2006 and 2018 the number of papers involving international collaboration at world level multiplied by 2.20 while national collaborative papers multiplied by 1.66, confirming that the global network grew more quickly overall. Table 2 and Figure 2 indicate that the volume of (though not in every case the proportion of) international co-authorship increased in all 42 countries while the volume of solely national co-authorship increased in all but five countries. The broken line in Figure 2 normalises patterns across the 42 countries. The location of the dot for 'World', relative to the normalising broken line, indicates that there was a more rapid growth of international co-authorship in the leading 42 nations in Figure 2, relative to the growth of national co-authorship, than in science as a whole. Above the broken line, scientists increased the volume of international collaboration, relative to the increase in national collaboration, by more than did scientists in the 42 countries overall. That is, they increased international linkages, relative to domestic linkages, at a faster rate than did most of their peers. Over half the European countries were above this line, indicating the outcomes of increasingly intensive collaboration within the European

Research Area, which by encouraging cross-country collaboration replicates the forms of a internally focused large federal national system.

The number of nationally collaborative papers more than doubled in the case of scientists from Malaysia, where it multiplied by 7.76, Iran (5.38), Russia (5.14), Pakistan (5.10), Egypt, India, China, Saudi Arabia, Thailand, Chile, Portugal and Brazil. In all these emerging systems national government was building national scientific capacity during the period, albeit with varying degrees of effort. The data pinpoint those countries where national collaboration was a relatively high priority, compared to international collaboration. In the three countries below the unbroken line in Figure 2, national co-authorships grew more rapidly than international: Russia, India and Thailand. (Note that in Russia measured national collaborations were boosted when scientists in the Academy of Sciences were newly affiliated with universities during 2006-2018, creating apparent additional collaborations through individuals' joint affiliations). There was also near balance between the two kinds of growth in South Korea, Mexico, Argentina, Iran and Malaysia. In all eight of these systems the relative priority given to national collaboration exceeded that in most countries. China and Egypt, and in Europe, Portugal, where science has emerged more recently than in most other Western European countries), have also engaged in especially robust national network building, while at the same time expanding international collaboration at a more rapid rate than the growth of national collaboration.

In emerging systems advanced internationalisation appears near mandatory. In all such systems in Figure 2 except those of Russia, Mexico and Argentina (each of which might dispute the use of the term 'emerging'), international co-authorship grew rapidly between 2006 and 2018. It multiplied by three times or more in the cases of scientists in Saudi Arabia (17.62), Pakistan (10.57), Malaysia (8.43), Iran (6.10), Egypt (5.89), China, South Africa, India, Chile, Brazil, Australia and Singapore (NSB, 2020, Table S5A-32). Only the last two on this list were mature systems throughout the period. (Note that in Saudi Arabia international collaborations were boosted by mass signings of part-time foreign research leader faculty to improve the global ranking position of Saudi higher education institutions, especially King Abdulaziz

University: see Gringas, 2014). The data also identify emerging countries where international co-authorship has developed especially rapidly compared to the growth of domestic co-authorship: Brazil, Chile, Turkey, Saudi Arabia, Pakistan and South Africa.

The established (mature) science systems in Western Europe, North America and Japan saw relatively slow growth of nation-only co-authored papers between 2006 and 2018. In some mature systems – Greece, Finland, Japan, the UK and Taiwan – national co-authorship declined in absolute terms and evident network dynamics continued to play out only in global science. In most European countries the number of internationally co-authored papers by national scientists at least doubled, and among US scientists, national co-authorship multiplied by 1.05 while international co-authorship multiplied by 1.91. Among the more mature science systems in Figure 2, Singapore, Taiwan and Australia saw the most pronounced shift in priorities towards international networking. In Taiwan national networking decreased (0.97) while international multiplied by 2.49. In Australia the numbers were 1.54 and 3.03 (NSB, 2020, Table S5A-32). As noted, the global/national distinction is not important in Singapore: nation-only collaborations between its two globalised universities are well placed in global science. International networking grew modestly in Japan, where the growth figure of 1.41 for international networking was the lowest for all countries in Table 2 in the 2006-18 period, and in France, Germany and Israel.

***Other studies.*** In Europe all of global, regional and national effects can be compared. Frenken (2002) investigates the integration of European science by comparing actual networks to a potential random distribution. He finds that in 1993-2000, prior to the data in Figure 2, collaboration within Europe became more evenly distributed, there was less bias in partner selection; large robust national systems exhibited the highest degree of integration; and there was a 'strong bias towards intra-national collaboration' (345). European integration was not at the expense of intra-national collaboration (358). The UK, Germany and France, with the most scope to develop new edges within the region, 'exhibited the highest degrees of integration in Europe … large countries benefit from scale effects that trigger European collaboration' (354-355). One reason was that their national languages were more widely used within Europe and in the rest of the world than was the case for the smaller national systems (356). Frenken et al. (2009) confirms the earlier results and finds that all else equal, scientists in larger national systems were also the most prone to collaborate internationally (224). The 'strong correlation between the size of a country and the level of its integration' (354) is visible also in the US where national science is exceptional in both its extent of integration with other countries' science and in the robust identity and scope of the intra-national collaborative network. These outcomes 'point to the persistence of national science systems' (Frenken, 2002, 345) and conform that national systems can be both internally robust and externally engaged. Kwiek (2020, 9), focusing largely on Europe, notes that between 2009 and 2020 the worldwide proportion of papers that involved international collaboration rose by 5.9 per cent while the proportion of papers that were nationally collaborative rose by 4.7 per cent. In EU28 countries the international collaboration share rose by 10.6 per cent while national collaboration share fell by 0.5 per cent, though in most EU countries the absolute number of these papers rose as Figure 2 suggests. Kwiek also notes that the EU13 countries, that joined more recently and whose science systems have mostly emerged later than those of the original EU15, the national collaboration share role by 2.0 per cent, consistent with many other emerging systems.

In a review of international co-authorship since 1970, in 48 leading science countries in paper volume, Olechnicka et al. (2019) report that in 35 countries there was a marked and similar increase in the international proportion of papers. In each case the shape of the curves was much the same: the proportion of internationally coordinated papers rose in line with the worldwide tendency. Many of these countries had mature national science systems in which global connects multiplied continuously. Others were emerging systems where international links were substituted for national infrastructure (Chinchilla-Rodriguez, Sugimoto and Lariviere, 2019, p. 3) and scientists engaged in international collaboration were more likely to be positioned as followers (Olechnicka et al., 2019, 103). Chinchilla-Rodriguez, Sugimoto and Lariviere (2019) remark that smaller countries like Azerbaijan, Peru and Panama 'depend almost exclusively on international collaboration for their output, with low degrees of domestic collaboration and sole authorship' (5), suggesting insufficient nationally-built capacity. The exceptional 13 cases identified by Olechnicka et al. (2019) are China, South Korea, Taiwan and Thailand in East and Southeast Asia; Russia, Poland and Romania in Eastern Europe; and Pakistan, India, Iran, Turkey, Tunisia and Brazil (80-83). Each of these 13 science systems, largely located in medium-sized or large countries, were built mostly after 1990, albeit rebuilt in Russia after the collapse of the Soviet system. In all these emerging systems except Taiwan the rate of growth of total papers exceeded the world average rate of growth after 2000; and in all cases national collaborations grew vigorously as the national science system developed. This modified the upward trajectory of the internationalisation curve. While in all these systems internationally co-authored papers increased markedly, as they did almost everywhere else, nationally co-authored papers also increased markedly (though again, Taiwan was an exception to the pattern). Table 2 shows that in ten of the 13 systems identified by Olechnicka et al. (2019) – Iran, Russia, Pakistan, India, China, Thailand, Brazil, South Korea, Turkey and Poland – nation-only co-authored papers grew by at least 50 per cent between 2006 and 2018 (NSB, 2020, Table S5A-32).

This group of strongly nation building countries shows itself as distinctive in other studies. Chinchilla-Rodriguez et al. (2019) note that China, Iran and Brazil have large systems, a lower proportion of total papers entailing international collaboration than is the case in most other systems, strong national networks and regional or global leadership roles (6). In their study of high energy physics Jang and Ko (2019) also identify China and Iran as countries following an 'independent' trajectory, with emphasis on national system-building, though the growing role of collaborative infrastructure meant that all national systems became more internationalised after 2010. Choi (2012) focuses on 'new rising stars' Turkey and Korea, whose shared trajectory, underpinned by government investment in R&D, was national system building followed by accelerated international collaboration and increased global degree centrality (35-39). Choi finds that in global science, 'dependence' on the 'core actors', meaning the Euro-American systems, is 'slowly declining' and predicts 'new clusters of the global knowledge network and, as a result, more diverse knowledge (39).

Maisonobe at al. (2016), who investigate patterns of collaboration within and between cities between 2000 and 2007, highlight the growth of intra-national collaborations in countries in which science at scale was then recent: China, Taiwan, India, Iran, Turkey, Greece, the Czech Republic and Brazil. They also identify a pronounced growth of international collaboration in the English-speaking countries (1029). Notwithstanding the inclusion of Greece and Taiwan, where national networking slows after 2007, among the national capacity-building systems, these findings are generally compatible with Table 2 and Figure 2. In developing capacity China and the other countries in the strong nation-building group have pursued a dual strategy, simultaneously working both kinds of science system. They have been effectively globally engaged but seem to be only partly dependant on the global system. Building national infrastructure enables them to strategically select and optimise global engagement, while they pursue global partnerships in areas that catalyse or complement national capacity. The dual strategy is underpinned by funding. Chinchilla-Rodriguez, et al. (2019) note that countries with higher investments in R&D ‘are more scientifically independent’, have a higher ratio of national to international collaboration (1, 6), have scientists more likely to take the lead author role in collaborative papers (6) and are more likely to garner higher citations when their scientists are lead authors.

National policies articulate network dynamics in negative as well as positive ways. Desultory funding and coordination (e.g. India and Poland); or, in mature systems, the slowdown of funding growth amid the global expansion of science (e.g. in Japan and Taiwan), can limit not only what nation-building in science can achieve but also the material capacity of scientists to collaborate globally. The limitation is more decisive in national rather than global networking because leading researchers who generate a disproportionate share of highly cited science often operate partly independent of their national systems.

In sum, all nations utilize both internationalisation and national capacity building but vary in the extent to which the outcome is ultimately realised in nation-to-nation networking and as autonomous agency on the global scale. It can be theorised that these variations are a function of strategy, policy and investment and also size.

Small countries may have little choice but to be heavily dependent on internationalisation in the evolution of their science, while larger ones can vary the extent to which they focus on establishing robust cooperation at national level across the range of research fields. It is noticeable that with one exception, of the national systems that have emerged in the last thirty years, those that have exhibited robust national networks and generate a significant body of globally cited science from national collaboration are relatively large in size and for the most part are strong national investors. The exception is smaller Singapore, where there are relatively few potential national co-authors but the level of national wealth has allowed national science to build quickly into forms paralleling the strong small European systems in Switzerland, Austria, the Low Countries and the Nordic world: highly internationalised scientific units supported by strong national infrastructure, personal and systemic agency, achieving high quality and quantity output.

However, these generalisations are not the whole of it. The potential for national variability should be emphasised. Nationally-based science is more or less connected, more or less self-focused, more or less autarkic on a country by country basis. Cases such as India, Japan and Russia are a reminder that at any point in the process of system evolution the balance between national and global collaborations can vary by country and over time. Further, there is always potential for national systemic factors to play out in the patterning of global collaborations, for example in the selection of geographically adjacent or culturally compatible partners, as noted above – which is more likely to happen when selective cooperation is fostered by national or European policy.

Nevertheless, despite the scope for strategic variations, the comparison between the two kinds of networked science, global and national, is consistent with the idea that each may advance simultaneously without retarding the other. If for some persons a national focus may substitute for an international one, it seems that when most scientists follow cognitive trails, or develop their careers, they follow opportunity rather than location.

## Spatiality and scale in science

In addition to global, national and local there are further scales in networked science. Scientometric papers use various combinations of multiple scales, as will be discussed. The pan-national regional domain in Europe is framed by law, regulation and financing as well as culture, and constitutes collaborative research on a large scale (Frenken, 2002; Kwiek, 2020). There is a multi-sector inter-governmental framework that facilitates cooperation in science in the ten member countries of the Association of South-East Asian Nations (ASEAN). In other world regions, inter-governmental machinery is less determining and pan-national cooperation rests on common culture and historical experience, as in the intensive co-authorship between scientists in Latin American countries, writing in English (NSB, 2020). There is also a regional scale located inside nations, which in some cases is framed by formal federalism (Carnoy et al., 2018); cities as regions (e.g. in science studies Maisonobe et al. 2015), and more informal cross-border regions that are based on geographically contiguous units, for example the Barents zone of Arctic cooperation in higher education discussed by Sundet (2016). The local scale can be understood in terms of differing units, for example scientific organisations such as local universities, or local groups of researchers.

What is scale? Herod (2008) remarks that in the study of human geography ‘scale’ is seen in two ways: as a material domain, or as a mode of perception and understanding. The present paper combines the two. Critical theory argues that there is a material reality prior to and independent of human perception of it. Nonetheless, that reality is appropriated only by perception; and acts of perception and understanding can also have shaping effects (Sayer, 2000). Hence geo-spatial scales have materiality – including the material effects of social structures – and they are also domains of understanding, imagining and normalisation. It is important to ensure that interpretation and normalisation do not overwhelm the materiality of scale. As will be discussed, this happens in some of the literature on science.

Geo-spatial scales are not equivalents of each other at different levels of aggregation and reach. They are heterogenous, being distinctive in kind. Structure and materiality vary between scales. The dynamics of global, national and local differ from each other, and they both co-exist and are irreducible to each other. Arguably, the materiality of the global scale is naturalised by the planet itself and its interdependent eco-system. The global scale is also socially structured in material terms by global communications networks and transport grids. In contrast, the nation is an 'imagined community' (Anderson, 2006) with no essential materiality. It has been created solely by human action and social relations. Nevertheless, its agents bring a potent materiality into being through territory and institutions, and it is regulated by abstract structures with determining force, including laws, hierarchies and economic transactions. The nation is also open to arbitrary remaking by agents, and routinely normalised, not just by politics but in much of social science. The nation is not natural, but is powerful in shaping both contemporary society and understandings of it.

**Transpositionality**

When the 'glonacal' method (Marginson and Rhoades 2002) is used as the explanatory framework, no geo-spatial scale is always or necessarily dominant. In the real world the primary causal scale or scales, the scale in which actions develop with the capacity to resonate in other scales, tends to vary by place and can change over time (Marginson, 2010). Multi-scalar spatiality is *always* contextual. For example, during the Covid-19 pandemic, in countries like UK that maintained an open border the global spread of the virus was determining; while countries able to seal themselves off effectively, such as New Zealand, could impose a national causality on the incidence of the virus. The glonacal framework allows global relations to emerge without privileging the global or losing the shaping potential of drivers in other scales. 'Both aggregate causality on a macro-level and individual agency on a micro level are legitimate angles, and both are necessary for a full picture' (Conrad, 2016, p. 160).

At the same time, as human geographers state, leading scale is also a function of perspective. All spatial position, including scale, generates a partial picture in which the particular positional lens in use (in this case global, national, local etc) tends to privilege phenomena pertaining to that lens. 'By changing the unit of analysis of operation at the reflexive level one obtains a different perspective on the system under study' (Etzkowitz and Leydesdorff, 2000, 114). Conrad (2016) makes a similar point: 'The choice of scale always has normative implications' (156). For example, when empirical observation of science is framed by the national scale, observation highlights identified national phenomena in science (e.g. comparative national output), and diminishes awareness of cross-national activity (e.g. the worldwide network of scientists identified by co-authored papers) except where this activity falls within the boundaries of the nation (e.g. the number or proportion of co-authored papers that are written by national-citizen scientists). This points to the value of exploring more than one scalar perspective and combining those perspectives, the 'trans-positional' method (Sen, 2002, 467), so as to broaden understanding of the relational terrain. In part the benefits of trans-positionality can be achieved when reviewing studies developed from differing scalar perspectives.

By the same token, when perception is confined to only one scalar lens, the resulting picture is not just limited, it can be misleading. The normative globalism of the 1990s, discussed above, was achieved in part by unduly diminishing the national scale and its causal weight. However, the more prevalent limitation in the study of science, and of many other social phenomena, is that the national scale is so powerful in governing thought that many find it hard to see a separated global scale at all. 'Methodological nationalism' is grounded in the belief that the nation/state/society is the natural social and political form of the modern world' (Wimmer and Schiller, 2002, 301; Beck, 2005, 43-50; Shahjahan and Kezar, 2013). Through the methodological nationalist lens, global phenomena can be only understood as functions of the nation and observed within the national scale. Associated with methodological nationalism is what Conrad (2016) calls the 'internalist' fallacy, in which national societies are seen to entirely determine their own affairs, generating 'explanations that slight or even completely disregard external influences and factors' (88), such as cross-border passage and connections, and world-level systems such as science.

In a globalised sector like science, to confine perception solely to the national scale is to decouple understanding from the real world. Yet this is common. Chinchilla-

Rodriguez et al. (2019) remark that the same data on cross-border research collaboration can be interpreted using methodological globalism, which emphasises the combined benefits of international networking; or methodological nationalism, which emphasises competition between national science systems (1-2). Different scientometric papers veer between these two one-sided interpretations. Some authors move between one perspective and the other within the one paper. It would be more challenging to adopt Sen's transpositional method; to attempt to integrate the insights generated from more than one scalar starting point.

**Asymmetries when using scale**

Nevertheless, a problem for research on science is that global and national activities are not equally visible in empirical terms, and also that global and national activities are not equally recognised. These two points are not the same; in fact the two asymmetries work in the opposite way to each other. This goes to the earlier point about scale being both a material domain, and a mode of perception and understanding. In material terms global science is covered more completely than is national science because the comprehensive bibliometric collections comprise data on global outputs and networks, and not all national scientific output finds its way to the global bibliometric repositories. Using such data, the materiality of global science is apparent, while that of national science is less completely so. However, in terms of perception and interpretation, national science is more often and more fully acknowledged than is global science. In fact, some scholars redefine scientific phenomena in the global scale as properties of the national scale, so that global science as such is not perceived at all. That is, the mode of perception of scale trumps the mode of its appropriation as materiality.

The point requires a fuller explanation. First, the material domain of scale. While bibliometric data provide comprehensive coverage of global activity in science, including the output of papers based on collaboration between authors from the same nation that enter the global pool of knowledge and hence are part of both systems, those same bibliometric data bases are radically incomplete in recording national activities, relations and outputs that do not enter global circulation of knowledge, especially non-English language science. Second, the domain of perception, interpretation and understanding. National science systems are regulated by prominent national agents, bound by policy, rules and resource configurations, and associated with institutions that are leaders in national context. National identity permeates social life. It has a taken for granted character. Perhaps national science in the form of nationally located intellectual work appears more coherent than it really is in material terms, and certainly more specifically and solely national than it is in reality. In contrast, global science is more decentralised, less formal. While global persons, collaborations and journals are visible, the same persons and groups of scientists who constitute global science are mostly present (and often prominent) in national systems. Many observers perceive them in solely national terms. Their globality is often overlooked. Much of what is seen as national science is also global science, and some is not national at all, but the idea that some persons, relations and scientific outputs could be *both* global and national at the same time (multiple objects) is not well understood.

Figure 1 (above) sets out the problem in diagrammatic form. In studies of science the boundary lines between global and national, and the content of the large overlap between them, in which the same scientific output and personnel are part of both systems – the zone of multiple objects in Figure 1 – are rarely discussed. As noted, it is not just internationally co-authored papers that enter the global science system. In many nation-only collaborations, the scientists respond to global science and their work is cited beyond national borders, being part of the common global knowledge. These papers should be distinguished from national papers directed to a national conversation that falls outside the global conversation altogether. There is also another question about the zone of multiple objects in science. The extent to which global papers become part of specifically national conversations on a country-by-country basis also varies. This overlap is mostly uncodified, though it can be explored using citation analysis.

As will be discussed, many studies of science focus on comparisons of national system performance in science, following seminal papers by May (1997) and King (2004). However, rather than undertaking the difficult task of disaggregating scientific activity and output so as to separate that which is nationally determined from that which is globally determined and cannot be solely ascribed to scientists from one nation, researchers mostly take the global data and arbitrarily allocate co-authored papers on the basis of the numerical proportions of nationally identified authors (e.g. a paper with three authors from one country and one from another is allocated on a 0.75/0.25 split). To allocate the common global data to different 'national containers' (Shahjahan and Kezar, 2013) on the basis of classification, treating the local and national as subsets of the global, is to follow the logic of scale invariance. It is to miss the heterogeneity between global science and national science, and therefore fails to address what holds them together, the way they provide conditions for each other despite, or because of, the heterogeneity between scales. When all science is allocated to one or another national system, then the global system, despite its dynamism as a self-producing system, distinct from separated nodes, vanishes from sight. Cross-border collaborations are combined functions of each national system capacities, *and* the separate global system. The relational and cumulative character of knowledge is lost, as is the differing roles played by scientists within the collaboration and the differing experiences of cooperation. Further, to attribute cross-border collaborations as simply a function of national attributes, national causes, is to commit the 'internalist' fallacy identified by Conrad (2016). Reworking international collaboration data from the global science system by framing science as a competition between nations wipes from view the collaboration intrinsic to the extraordinary expansion of the global science system. It is also a strangely self-contradictory method, negating the basis on which the data were generated and collected. A parallel problem dogs the work of Packalen (2019) who uses citation-based investigation of whether scientists build on novel or established ideas to compare national performance, oblivious to the fact that the allegedly separable national performances derive from flows of knowledge where it is impossible to know where nations begin and end.

Bornmann et al. (2018) critique studies in which the authors 'look at a country as an entity in a global set of similar entities. They do not consider interactive aspects' (933). See also the reservations of May (1997), discussed below. When global data are treated in a standardised, homogeneous way so as to ascribe them to one nation or another, this not only obscures relations of power in global science, it conceals anomalies. For example, nominally national shares of co-authorship also vary in the extent to which they are ‘national’ at all. Is a sole-authored paper from a government laboratory in Sao Paulo as exactly twice as national as one from a laboratory in Stanford where a Brazilian doctoral student is co-author but the paper is defined by the local US professor? Yet using this method, international papers are seen as ‘national’ regardless of the extent to which national identity or national context was determining in creation.

The standardised treatment of global data as representing national science blocks from view the global science system, the specificity and diversity of national and local science, and relations between one national science system and another. Yet works that are nation-bound and do not appear as a measured part of the global conversation, such as papers in languages other than English, also fall outside view. Whether the blockage is achieved by refusing to acknowledge the reality that is seen in the data (the global), or the reality is excluded by the data collection methods used (part of the national), the effect is the same. An incomplete picture of global and national science results; and the relational, multiple and cumulative character of knowledge, which in real life is often indifferent to borders, is lost.

**Scale in scientometrics**

Researchers in scientometrics mine bibliometric data on publications, collaboration and citation, primarily from Web of Science and Scopus, to study patterns in science (see reviews of the field by Mingers and Leydesdorff, 2015; Chen and Chen, 2016; Patelli et al., 2017; Citron and Way, 2018; Chen et al., 2019). As noted, these scholars often use social network analysis (Scott, 2017). Bibliometrics generate large data sets inclusive in reach but on the basis of a small spare group of indicators. These data sets do not present ‘knowledge’ as such but various proxies for knowledge and knowledge-related behaviours. Some of the central aspects of knowledge that distinguish it from most other activities, including its collective character, the way it joins the past and present, and its extraordinary speed and fluency of movement, are scarcely visible in the raw materials of scientometrics. Those raw materials have a brilliantly wide reach, yet the base of that reach is narrow, like a tightrope walker; and the indicators are standardising, ironing out contextual variations. Quantitative researchers generate large-scale correlations, in which bibliometric indicators are mapped against scale or identity – nation of origin is the most frequently used variable – and science is compared between sites and/or over time. In the absence of a thicker, more theorised, complex and contextualised picture, the resulting findings are then mobilised as potential causal explanations. Researchers vary in the boldness of their assertions about causality. In related work, as noted, many researchers use bibliometrics to develop national comparisons of performance in science, the largest single component of the literature. Researchers also disaggregate global data on the basis of country, region, city or institution.

Scale has more than one use in scientometrics. First, there is scale in the normative sense discussed above, when it frames observation and the sense of the possible. The main scales in this respect are the global, which is often disaggregated to particular disciplines or scientific topics; the pan-national regional, mostly in Europe; the national, the most utilised normative scale; and the local-institutional, meaning the university or research institute as organisation. Second, there is scale as data set, as in global data or data specific to one nation or institution. Third, there is scale in terms of units (categories) of analysis. All three uses of scale can be in play together – for example in a study using global data on papers in engineering research, in which nations are compared on the basis of the performance of their leading universities. The normative scale is the national, the purpose is national comparisons; the data set is the global discipline; and the unit of analysis is the institutional.

Nevertheless, the tools used in scientometrics are not always sufficient to the task. Bibliometrics and network analyses alone struggle to encompass, conceive and observe science in spatial terms and especially to map the relations between the primary global and national science systems. Once collaboration growth, internationally mobile researchers, joint or multiple institutional affiliations, and the multiple international basis of citations, are all taken into account, ‘it becomes increasingly difficult in bibliometric analysis to separate clear country effects’ (Bornmann et al., 2018, 942; Adams, 2013, 2).

There is some explicit discussion in scientometrics of the distinction between the national and global scales. For example, Wagner et al. (2015) discuss potential tensions between scientists loyal to their global colleges and collaborative lines of inquiry, and national governments and agendas in science (see below). Bornmann et al. (2018) discuss the distinction between national and international collaboration, noting it is not a constant: 'the tensions and trade-offs between international and national perspectives can be expected to differ among disciplines' (931). National specificity matters more in sociology than physics (931-932). Researchers are under pressure 'to maintain both a national and an international profile'. Scientific elites mediate the tensions between 'national resources and international mainstream research' (932). Activities in the two domains interact (933). Further, country-affiliation is a questionable concept. The researchers cite a study in Denmark which shows that in six out of ten cases the specific research is affiliated with at least one other country, and, 40 per cent of recruits into Danish research posts have foreign citizenship. Bornmann et al. (2018) use citation patterns to identify papers in the Netherlands and Germany which both draw on national authors in citation and are less cited in the global literature, pointing to islands of national knowledge flows that are partly detached from worldwide exchange.

Scientometrics does not satisfactorily use scale and still less does it resolve scale conceptually. There is wide variety in approach; and sole reliance on global data, normative globalism and methodological nationalism stymie understanding in different ways. In most studies that use multiple scales, scale invariance irons out the qualitative variation between the scales. Arguably, to adequately explore relations of global and national in science it is necessary to combine the bibliometric data sets and social network analyses (Scott, 2017) used in scientometrics with further empirical data on science outside the bibliometric collections, and theorisations developed from the sociology of networks and the political economy of science. The lacunae do not stop scientometrics from generating interesting if partial insights into the global and national science systems. At best the use of multiple scale in scientometrics, with its far-reaching data set, generates significant insights into distance, locality and networked connections in science – especially when the powerful category of 'nation' is dethroned so that the national scale becomes just one scale alongside others and the fuller materiality of science can emerge. At worst the unresolved definition of scale and the normative nationalism in scientometrics sabotage the intellectual insights of the research. Examples of both kinds of work will be considered.

**Multiple scales in scientometrics**

In a review of 'spatial scientometrics' Frenken et al. (2009) summarise approaches to space and scale in 41 papers. In terms of data set 21 studies are global in reach, though the number of countries that are included varies between studies, and eight are European wide. However, in most of the studies the normative scale is national. Only seven papers express spatial variation in terms of a single global space, measuring distance in terms of kilometres. Others privilege the nation by using the national designations of authors or the foreign/not foreign distinction. In terms of primary unit of analysis, 11 of the papers use pan-national region, 27 of the 41 papers use 'country' (20 use only country), and two use city. None of the 41 studies use institutions as the unit of analysis. In relation to topic, much the largest group of papers focus on comparisons of performance, 'differences between countries and between regions in terms of their publication output and citations.' Smaller groups of papers investigate 'spatial biases' in the bibliometric data 'in collaboration, citation, labour mobility and conference attendance'; and investigate the higher citation rates associated with international co-publication when compared with national co-publication (226).

Seven of the 41 papers listed by Frenken et al. (2009) use country and pan-national region together. Other studies go further in using multiple scales. Helibron (2013) theorises social science as a 'four level structure' that includes the local, national, 'transnational regional' (European) and global (685). Wagner and Leydesdorff (2008) understand science as 'a system that now includes local, regional, national and global levels of order' (323). Their work mostly uses global/local and global/national couplings. Individual studies from them and their collaborators group move between purely global approaches (e.g. Wagner and Leydesdorff, 2005) to studies that also re-articulate the bibliometric data on global science through national categories (e.g. Wagner et. al, 2015; Wagner et al, 2019).

In investigating the effects of different national system configurations in research on photovoltaics, Graf and Kalthaus (2018) model three kinds of networked relations, each involving differing agents: relations between national states/systems at global level (‘macro’), between institutions like universities at the national level (‘meso’), and between scientists at the global or national level (‘micro’), noting that ‘the network structures at different levels of aggregation influence each other’ (3). This is one of the most developed investigations of scale, as it defines each scale as a distinctive relational space rather than as an arbitrarily defined container of indicators, but it is again stymied by being confined to the single global data set, and assumptions of scale invariance. The micro is nested in the meso, and the meso in the macro, as with Russian matryoshka dolls. This implies that scientists’ global connections are articulated in vertical fashion through the institutional and national; and that ‘global embeddedness’ is a national phenomenon, shaped by policy, funding and the regulatory regime. However, in the real world the matryoshka nesting is incomplete and local scientists often work directly to the global without passing through national regulation, or the control of university managers, sometimes to the chagrin of the latter.

Grossetti et al. (2013) explore the national and city scales together, using Web of Science data for 1987-2007 to determine change in the extent to which scientific activities are concentrated in large cities within nations. They identify a ‘generalised trend towards decentralisation’ (2223) within countries, with lead cities becoming less dominant in their share of total national papers published, paralleling the diffusion of scientific activity among a growing number countries (2225). Maisonobe et al. (2016), working with the same data set over 1999-2001 and 2006-2008, compare national inter-urban scientific collaborations with those on the global scale. They confirm Grossetti et al. (2013) on the extension of urban networks. ‘Scientific relationships developed simultaneously between all the cities of the world system’ (1033). They also find that in most countries national collaboration between cities increased faster than international collaboration. They conclude that emerging country systems are focused primarily on national collaborations, while ‘historically central countries’ such as the US and UK engage in ‘international development … without diminishing their internal cohesion’ (1029). They also argue that too much attention is given to major cities as international hubs, relative to their national roles, that are fostered by governments (1034). ‘National systems of research have been strengthening during the 2000s’ (1025), while concentrated collaborations between cities in sub-national regions are also significant (1033). Their test of a globalisation trend is that it must be both ‘sizeable and unilateral’ (1020): the possibility that both global convergence and national networks could advance, and each tendency might support the other, is not considered.

Some papers identify intersections or correspondences between scales. In their study of salary and prestige in US higher education, Melguizo and Strober (2007), working outside scientometrics, state that ‘academic institutions seek to maximise prestige’, while ‘faculty members are rewarded for enhancing institutional prestige.’ (633). There is cross-scale symbiosis between faculty and institutional goals (635). Kwiek (2020) makes a similar point about science in Europe (4). The correspondence between the two kinds of prestige seems to be especially enhanced by global activities, which helps to explain the ubiquity of the reception of university rankings (Hazelkorn, 2015) and norms of internationalisation.

Other papers, in scientometrics, compare scientific activity in different scales. The potential of this kind of differentiation is limited, as scale is usually read in scale-invariant fashion as ascending levels within a common data set – it is assumed that there is one macro set of science, described by global bibliometrics, and that everything local or national is contained in that global set. Solely relying on bibliometric data, rather than a theorised assemblage of scientific relations, renders inevitable the classification-driven assumption of scale invariance. Once scale invariance has been assumed the possibility of heterogeneous scales is blocked, as is the potential to consider any reality invisible to global bibliometrics.

Bornmann et al. (2013) and Frenken et al. (2017) focus on the research performance of universities, as measured using global scientific indicators, while attempting to separate and weigh against each other the respective roles of national, disciplinary and local-institutional factors. Their normative scale is institutional, their data set is global, and their primary units of analysis are national and institutional. The similarities and differences between the two studies are emblematic of much of the literature. It is worth looking at them in more detail.

The national and institutional are each proxied by a spare set of indicators which differ in each case. For Bornmann et al. (2013) the indicators of nation are per capita GDP, geographical area and population; the indicator of university is size as measured by number of publications (1650). The dependent variable is the proportion of published papers in the top 10 per cent of their field by citation rate. They find that four fifths of the statistically identified variance between universities in citations is explained by the national factors not the single institutional factor; and differences between universities are 95 per cent derived from variance between disciplines in high citation work, with only 5 per cent explained by differences between the universities as universities (1655-1656). Franken et al. (2017) use a larger set of indicators for institution including size, age, disciplinary orientation and city location, but in relation to nation confine themselves to the single category of country location. Their dependent variables are the number, not the proportion, of high citation publications, international co-publications and university-industry co-publications. In contrast to Bornmann et al. (2013) they find that country effects are modest in explaining differences in institutional performance, while institutional size and discipline mix are significant: larger universities, and technical universities strongly focused on engineering and related fields, are disproportionately better at generating highly cited papers. In both studies the choice of indicators determines the findings, as Franken et al. (2017) note (867). Franken et al. (2017) also rightly state that their outcomes variables ‘provide a limited and incomplete assessment of the phenomena of interest’ (868). These studies suggest that there is little gained by exploring scale using arbitrary proxies within the global data set. Further, as each study notes, contextualisation, which they do not attempt, is essential when comparing science systems. However, Franken et al. (2017) do make a useful point about the ‘questionable implicit assumption of a single global system’ inherent in the global ranking of institutions, in which the focus is solely on the institutional scale (860); and Bornmann et al. (2013) note that rank ordering universities is statistically contaminated by joint publishing between them (1657). Scale awareness can be helpful.

Hennemann et al. (2012) ask ‘which spatial scale has the strongest impact on science?’, international, national, or local (217). They find the relation between distance and the propensity to collaborate is stronger inside the nation than outside. At global level scientists collaborate freely anywhere through the Internet. Wuestman et al. (2019) compare the citations accrued by teams collaborating at the local, sub-national regional and national scales. They identify a strong bias to local collaborations and a bias to the national that diminishes as distance inside the nation increases. However, beyond the nation they too find distance unimportant; and when there is close knowledge-relatedness between cited and citing papers, scale has no effect on the potential for citation anywhere (see below).

A common use of multiple scale is to compare collaboration in the different scales in the global data set – authors from same institution, same nation, or international co-authors – interrogating the data in terms of the nature of the networks, paper volume, citation linkages, and citation quantity and quality. For example, Abramo et al. (2017) compare research productivity, as measured by papers and citations, in each of the three forms of co-authorship (international, national, local-institutional), for Italy only. The researchers do not define and discuss the meanings of the scales themselves. Again, the collaborative behaviours are compared on the basis of scale equivalence. Docampo and Bessoule (2019) compare the ‘strengths and weaknesses’ of science in terms of national systems, and institutions (1207), though the main discussion is about the former. It is one of the many studies that investigates global science not in terms of relations but as discrete and comparable units of ‘performance’ aggregated in mosaic fashion. Further, the risk in dividing the single global data set on the basis of scalar categories is that the categories themselves are seen as determining of the differences that appear. For example, when there is an apparent performative difference in national collaboration compared with international collaboration, to what extent is the type of collaboration determining of the variation in outcomes, or is it vice versa, or do hidden third factors determine the statistical association? What is truly at stake in comparing national collaborations and cross-border collaborations, which may involve almost the same scientists and body of papers? As noted, there is overlap between national science systems and the networked global system; and publishing scientists are active in all of the local-disciplinary, local-institutional, national and regional and global domains. In short, there is ambiguity in both the categories and their significance, and both aspects can vary between countries, over time and across disciplines.

Given that science systems operate in several scales, a multiple approach to scale must expand the range of explanation in science. Arguably, multiple scales are indispensable to understanding – provided that the notion of scale hierarchy is set aside; no one scale is universalised, enthroned as necessarily primary in all cases; and provided that the heterogeneous potential of scale is understood and factored in. However, most studies of global science fail to take a multiple approach to scale; and most studies that use multiple scales follow the logic of scale invariance. Single-scale approaches often universalise (totalise) the national scale. This perspective subsumes the materiality of global science, in that the data are reworked to fit the totalising scale. A further group of studies are able to strike a better balance between the chosen perspective on spatiality and scale, and materiality, thereby enabling the researchers to address the global science system and factors of locality and distance without abandoning awareness of other scales.

The next two sections of the paper will review the literature in scientometrics and multilateral comparison that totalises scale, mostly often by enthroning the national scale, and then studies that enable the global scale to emerge without essentialising it.

## Scale as a totalising perspective

Studies in scientometrics that totalise one or another scale focus on either the global or the national scale, though in most instances they are captured by methodological nationalism. These studies reduce one scale to the other, or arbitrarily displace one scale by the other scale, moving back and forth between different totalising scales within the same paper.

**Between methodological globalism and methodological nationalism**

A common kind of paper combines the ‘externalist’ and the ‘internalist’ fallacies. That is, it moves between absolute methodological globalism and absolute methodological nationalism. These papers begin with global bibliometric data and rework it in the form of national ‘shares’ of global science. The linking between these two discordant stages is a teleological narrative about global networks. It is assumed that collaboration within the global network *necessarily* has a positive effect on national scientific performance and through that, the global competitiveness of the nation in technology and hence the economy. Consistent with this approach the literature commonly assumes that openness to global relations has a necessarily positive influence on national science systems and are a good thing everywhere (e.g. Wagner et al. 2001); even though ‘nations do not have the same opportunities to access the global scientific market and the notion of openness works at different levels depending on the scientific capacities of countries and its [sic] ability to maintain and attract talent’ (Chinchilla-Rodriguez et al. 2019, 12).

Assumptions that all globally networked activity in science is positive, and positive in the same way in every case, are pure normative globalism. On this normative foundation the co-publication and citation data are arbitrarily assigned between countries and deployed to rank order and performance test those countries and their institutions. As noted, both the collaboration data and citation data are relational yet they arbitrarily assigned on an individualised nation basis. National ‘performance’, understood in terms of competition between nations, is discussed in combined tables that position countries against each other (multilateral comparisons) or is examined in terms of changes in the position of one nation over time (single nation studies). In both cases national categories are arbitrarily imposed on the global data and the relational character of those data snuffed out. Here normative globalism is radically displaced by methodological nationalism.

***International co-authorship.*** In the majority of cases authorship is multiple and the order of authors is ambiguous. Lead author might mean a greater authority in authorship, or a larger part of it, but how much so? Is it the authority of the leader of the group, the initiator of the work, the primary originator or interpreter of ideas, or the writer? Lead author roles are used as a constant in some comparative studies (e.g. Chinchilla-Rodriguez et al., 2018b) despite the fact that they have differing incidence and implication from field to field and discipline to discipline, where authorship conventions vary; and from country to country. In the case of emerging country authors, follower author positions may signify the alphabetical convention, a dependence in which the topic is determined by the author from the dominant country, a subordinated role within the research group, and/or a contribution of equal strength. It may be more meaningful to discuss with caution changes over time in the internationalisation of papers in nation X than compare the internationalisation of papers in countries X, Y and Z. But inter-country comparisons are very common.

The larger problem is the common normative bias in favour of international collaboration, as discussed. It seems that 'collaboration' is uniformly positive, conjuring up expectations of higher quality, productivity and greater scientific and other impacts. The association between higher rates of international collaboration and better science has become part of common sense in policy and public discussion of science, despite the potential for contextual differences and the vast variability of individual cases. This normative abstraction legitimates free comparisons of collaboration across all national research systems on a quantity basis. Such comparison functions as a calibration of virtue. With a small number of interesting exceptions (e.g. Abramo et al. 2017; Wagner et al. 2019), scientometric studies leave unquestioned the dominant belief about the formative relation between international collaboration and better science, and better effects of science, notwithstanding the leaps in logic that are entailed in this chain of reasoning. Outcomes in published science ('research performance') can be understood in individual, institutional or national terms (Abramo et al. 2018), and in terms of productivity or visibility. All of these aspects are linked positively to international co-authorship. Yet the association is not quite taken for granted. Perhaps its causal status is in doubt. There is unease about the narrative, judging by the fact that much effort goes into demonstrating it empirically: it needs to be continually reasserted. Studies of science repeatedly measure whether it exists and how it varies. The coupling of international collaboration and better science is like many social science norms. Great efforts are expended in showing that the casual relation exists, defining the conditions that enable it, identifying who is best at doing it, implying that it should exist and critiquing identified failure to make it exist, and developing proposals to install or reinforce it. Graf and Kalthaus (2018) summarise the literature: ‘There is vast empirical evidence that collaborative research leads to more valuable output than individual research’, though causality is ‘elusive’ (2).

In an influential pioneering study of ‘Global cooperation in research’ Georghiou (1998) sees informal collaboration among scientists as prior to national policies designed to foster cross-border collaboration. ‘Formal arrangements are beginning to catch up with the very substantial extent of “bottom-up” global cooperation’. In examining motivations for cooperation, the study distinguishes ‘between direct benefits to the research and indirect strategic, economic or political benefits’ (611). Following a detailed review of ‘formal arrangements’ he concludes by arguing that open international collaboration in science furthers the interests of nation-states (625). In subsequent studies, however, the relative roles of bottom up disciplinary networks and nation-state drivers are rarely considered. The nation-state element is mostly foremost. It is significant that there is much more research on national variations in international collaboration than on variations in collaboration by discipline, institution, culture or distance; and cultural proximity or the distance factor are often measured using the national designation as a proxy.

Many studies identify positive relations in one or both directions between on one hand international collaboration, and on the other each of productivity and visibility. For example, in relation to productivity, Muriithi et al. (2017, 4) establish a positive relation between collaboration and publication in Kenya. Zhou and Tian (2014) find that international collaboration performs better in raising academic productivity than do other forms of collaboration in science, all else being equal. However, a small number of studies differ. Abramo et al. (2017) find that while collaboration within the university or within Italy has a positive and significant impact on individual productivity, international collaboration is associated with a negative though not significant impact on individual productivity, except in three discipline clusters. Reversing the relation, research productivity positively affects the propensity to collaborate at international and national levels though not the propensity to collaborate within the university, in general and in some disciplines (1025-1027). Abramo et al. (2018) confirms that causality if it exists could flow in either direction. In Italy all increase in the performance of top scientists over five years can be explained by the fact that international papers have a higher rate of citation. Likewise, Kwiek (2018, 446) finds that highly cited researchers are more likely to collaborate internationally but again, nailing down a casual relation is difficult. Abramo et al (2018) find that leading scientists show the largest increase in international collaboration over a five-year period. Lesser performing colleagues show the largest increase in national or local collaboration.

In relation to visibility, 'solo papers do not contribute to the growth of the citation impact of scientific fields as multi-authored papers do' (Katz and Ronda-Pupo, 2019, 1059). Most studies suggest or outrightly assert that international collaboration raises research quality and/or visibility as understood in terms of citation (Frenken et al., 2009, 225; Kato and Ando, 2017, 677; Chen et al., 2019, 164; Woldegiyorgis at al. 2018, 64; Chinchilla-Rodriguez et al., 2019; Katz and Ronda-Pupo, 2019, 1049; Wagner and Leydesdorff, 2005; Wagner et al., 2017, 1634; STO, 2019, 76-77; Khor and Yu, 2016; Winkler et al., 2015; Cimini et al., 2016 in relation to Europe). A rare contrast is Chen et al. (2019) who find no relation between international collaboration and citation (163). Khor and Yu (2016) find that publications with multi-national collaborations have higher citations than do bilateral collaborations (1103). Morillo (2019) finds that internationally-funded work tends to have greater citation impact. International collaboration is associated with greater impact in Europe where funding schemes require multi-national collaboration; though again the question about causality remains: does the larger impact of internationally collaborative projects derive from the fact they are international or the fact that researchers and their project idea are selected on the basis of excellence, which is expected probability of impact? Chinchilla-Rodriguez et al. (2019) find that the scope to benefit from collaboration in citation terms is structured by science funding levels. In countries that allocate more than 2 per cent of GDP to R&D, collaboration of all kinds is associated with above average levels of high citation papers, and the difference between the citation rates of internationally co-authored papers and nationally co-authored papers reduces. In countries that invest less than 1 per cent of GDP in

R&D only international papers secure above average citations (6), in part because such collaborations often involve authors from a research stronger country.

It is clear that there can be more than one reason for these correlations between international collaboration and measures of outcomes (Chinchilla-Rodriguez et al., 2018b, 1498), and more so given the ambiguous character of citations, used as a primary indicator of comparative outcome, as will be discussed. There is also variation, in the association of collaboration and outcomes, by discipline (e.g. Chen et al., 2019, 161), status of institution (Khor and Yu, 2016, 1107) and in relation to the countries and individual scientists included. Kwiek (2020) finds that 'papers involving national collaboration have a higher impact on global science than international collaborations in only five countries' but two of these are the global superpowers US and China, indicating the potency of their national networks. The other three are France, Romania and Poland (16). Kwiek notes the nationally nested nature of the humanities. Citations are higher to domestically co-authored papers than to internationally co-authored papers in UK, France and Italy (15). Chen et al. (2019) make the salient point that scientists and/or countries engaged in international collaboration are prior selected on the basis of superior performance, raising doubts about the extent to which international collaboration in itself has added value to performance (163-164). In addition, these authors argue, few studies have focused on 'the factors and mechanisms' that may affect the impact of collaboration on performance both in general and in particular countries, or investigated the potential for mutual causality between the factors (163-165).

None of this halts the juggernaut. Even most of the sceptics do not remain out of line for long. For example, Cimini et al. 2016 state that 'it is necessary to point out that the presence of a possible cause-effect relationship between scientific success and international collaborations is still an open issue' (201), but by the end of their paper causation has become unqualified: 'Internationalisation emerges from our analysis as an additional fundamental parameter for the scientific development of nations' (210).

***Citations.*** Like co-authorship, citation data are ambiguous and many scientometric papers acknowledge this – yet remarkably, citation retains the status of an abstract universal positive. Waltman (2016) provides an overview of the use of citation impact indicators, and Tahamtan and Bornmann (2019) review 41 studies of citations between 2006 and 2018. This includes aggregate and disaggregated citation counts and studies that explore scholars' motivations for citation, using interviews and surveys. Citations are often mostly simply as a sign of valuation. The number or proportion of citations to papers from a particular research organisation or national system is seen as a sign of the standing of that unit. Yet the purposes of citations can vary markedly. 'Our review of the empirical studies demonstrates that a paper may be cited for very different scientific and non-scientific reasons' (Tahamtan and Bornmann, 2019, 1635; Patelli et al., 2017, 1230; see also Bornmann and Daniel, 2008). Aside from problems of self-citation and of negative citation (works that are undergo sustained criticism within a research field will appear as highly cited), are they expressions of cognitive debt, or relations of dependence, or collaboration and mutual support, or the field identity of the author doing the citing, or the building of status for the author, the paper and the research organisation? More than one kind of citation can occur in the same paper. Tahamtan and Bornmann (2019) identify two theories of citing behaviour. The first 'normative' theory, attributed to Merton (1973), assumes that 'scientists primarily cite their peers to give them credit' for cognitive reasons. The second 'social constructivist' theory suggests that the decision to cite may be based on many factors. Authors may cite other scientific works to strengthen their own claims to validity (Tahamtan and Bornmann, 2019, 1637). Tahamtan and Bornmann propose a model which combines the normative and social-constructivist (1638). But in the absence of a theorisation of the different purposes of citations and of contextual variation in the balance between them, citations cannot provide a single standardised 'currency' or system for valuing knowledge or its creators.

Citation data are used to measure the performance of both individuals and groups at any level of summation, in comparisons of national research performance, and in the global contest between 'World-Class Universities' (ARWU, 2021; THE, 2021; QS, 2021). All of the leading global university rankings rest on the shifting sands of this standardised measure of value, with its potential to affect different units in the comparison in variant and largely hidden ways. Most papers on science are untroubled by these difficulties. As in the case of interpretations of international co-authorship, some authors rehearse the problems of using citation data and then move ahead with the analysis of citation data as if the problems never existed. An example is Abramo et al. (2019) which advocates a new indicator, the 'balance of knowledge flows' (BKF), that uses citation flows in both directions to measure nations' comparative performance in research. In the discussion of method, the authors state: 'Since knowledge transfer cannot be observed directly one relies on proxy measures, notably citations. Citation linkages between articles is then assumed to imply a flow of knowledge from the cited to the citing entity… Citations in fact are not always certification of real use and representative of all use. Uncitedness, undercitation, and overcitation may actually occur' (2). However, no effort is made to respond to these problems in the design of the BKF indicator and they are unable to interrupt the claims made. The authors believe they have a winning idea and their prose is unstoppable, urging that 'the BKF can be part of yearly reports of science and technology indicators, aimed at informing research policy' (1).

Notwithstanding the ambiguities of citation data as a universal value, they are of interest because other than co-authorship data, keyword and keyphrase study of similarities and differences between papers in their contents, and webometric data on web-usage, they are the only large-scale common measure of flows of connection and recognition of ideas and works. For example, studies of the relationship between cited documents and citing documents, and their respective contents, field boundaries and/or further connections, enable a structural picture of the investigation of topics. People networks and content-based networks can be made visible and the relations between the two kinds of network can be mapped. Bornmann et al. (2018) develop 'citation concept analysis' which traces the citation impact of key concepts (1). Bornmann et al. (2018) use the identity of cited works to distinguish national from global patterns of science. Citation patterns can be used to trace the intersections between fields and conversations, bringing substance to the often overly normative discussion of interdisciplinarity including its genesis, shape and applications.

**Nationally-framed studies**

The use of the national scale as a normative scale both reflects and shapes a nationally-bordered perspective on science, its purposes and activities. As remarked, it is through such acts of power that the 'imagined community' of the national is created and sustained. From a methodologically nationalist perspective, national science, confined to matters visible within the national terrain, is the main science system that can and should be observed and understood. The effects of this reduction in the process of perception – the determination of what can and cannot be seen – must be emphasised. Phenomena such as global science, and national systems other than the favoured system, lie at the edge of nation-bound science or are seen (especially in US-based studies) as functions of it. Nevertheless, a feature of this genre of science studies is a lack of clear definition of what constitutes national science or a national science system – though the latter term is often used. It is as if national science is so commonplace as to be taken for granted. All of this leaves the problem areas undiscussed: the reliance on global bibliometrics that do not fully address the national, the national/global distinction, and the zone of multiple objects, the overlap.

Some scientometric studies express unease about 'nation' as a normative or sole category and as a unit of analysis, though mostly as a passing thought. Adams and Gurney (2018) state that 'international communications enable the very best research groups to work with one another without regard to national boundaries'. However, when researchers become 'inextricably intertwined with other research economies, it will become increasingly difficult for any comparative analysis of a country's research performance to identify a separate national component' (3). The final paragraph of Basu et al. (2018) on science in China shifts out of the national container used up to that point to state, apologetically, that 'there are many benefits of science and technology, regardless of where the R&D is done', and 'most of these benefits can accrue to everyone, regardless of their nationality' (267). Chinchilla-Rodriguez at al. (2018a) note that research collaboration is generated by individuals, not countries, and hence the analytical role ascribed to countries is inferred, though they make nations central to their argument from thereon (1487). Cimini et al. (2014) remark that the national comparisons that they generate 'are confounded to a certain extent because a large and growing fraction of scientific work involves international comparisons' (8), though they express their conclusions in terms of single nations. Packalen (2019) compares the recency of the citations used in biomedical science papers, which he calls the 'edge factor', on a nation by nation basis. However, 'the approach can be utilised to evaluate the novelty of research published by a journal or institution', and 'the novelty of individual scientists' publications', and the portfolio of projects supported by funding agencies (788-789). 'We selected countries as the unit of analysis because borders continue to influence scientist interactions and because many important science policy decisions are set at the national level' (788). The political role of the nation-state, more than the nature of scientific relations, sustains the central role of 'nation' in research on science. Politics is primarily national, so science is mostly understood as a phenomenon of the nation-state.

There are at least four types of nation-bound study. First, investigations that norm science as a branch of the national economy and focus on the relation between indicators of scientific performance (for example, high citation papers, or international collaborations) and proxy indicators for economic output or efficiency; or seek to measure the junction between research science and industry. A related set of work focuses on the efficiency of national or institutional science as understood in economic terms. Second, there are the many studies that focus on multilateral comparisons of scientific performance, at world, regional or bilateral levels. The large bibliometric collections are repeatedly mined using new inclusions, combinations, or angles, often in conjunction with national indicators external to bibliometrics such as GDP per capita or Internet use. It is easy to develop original studies given the many different ways that bibliometric data can be utilised. Third there are studies that focus solely on one national science system in scientific and economic terms. Fourth, studies that frame global network analysis in science by fixing nations as aggregated nodes – despite their size and internal complexity – and explore the relation between these nations-as-nodes. There is some overlap between the four groups of studies.

***Science as a branch of national economy.*** The concept of science as the bedrock of national industrial innovation is a meal-ticket so central to scientometrics, as a field of applied social science, as to constitute a form of common sense that is rarely questioned. In the manner of such policy-related norms, the economisation of science is treated as both an accomplished reality and an ideal to be achieved, the basis for reform policies and strategies. Cimini et al. (2016) make a claim for a 'science of science policy' that is focused on scientific output, and the outcomes of science in relation to financial inputs, and is especially focused on the comparative performance of nations:

> The science of science policy is emerging as an interdisciplinary field that aims at developing theoretical models and studying empirical evidence for the performance of scientific communities and individual researchers. This scientific activity can then help to develop policies for improving Research and Development (R&D) funding allocation and strategical decision making. Within the field, a critical issue has been that of identifying suitable quantities to characterise the research systems at the level of nations, in terms of scientific impact, development and competitiveness (Cimini et al., 2016, 200).

In this, the conventional way of thinking about science policy, what matters is science that signposts a pathway to capital accumulation, and capital accumulation within national borders. The 'science of science policy' is a significant reduction, in several ways: (1) in the real world science spills out across national borders, (2) capital accumulation also operates on the global scale, (3) the 'science of science policy' conceals from view the heterogeneity between circuits of knowledge and circuits of capital, and violates the autonomy of science. In this framework the role of the 'science of science policy' becomes to identify alleged linear cause and effect relations between science and economy, to measure efficiency in those relations and thereby help to enhance performance. Cimini et al. (2016) identify as 'fundamental aspects' of national research systems investment in research in higher education as a proportion of GDP, citations relative to paper volume, and the proportion of papers with international collaborations. Economic efficiency means 'turning financial input into bibliometrically measured output' (200). They argue that 'parallelism found between scientific and economic production can be seen as the natural consequence of the coupling and co-evolution of the different components of the innovation ecosystem' (210). Studies in the 'science of science policy' see science as part of a larger system within the economy.

Much scientometric research focuses on an expected relation between international collaboration in science, and national economic development and competitiveness. International collaboration is seen as a way to leverage global science and globalisation for national advantage; while in a reciprocal process, augmented national scientific capacity feeds back into the capacity to collaborate abroad and trigger further benefits. Most national science systems deliberately pursue this strategy. The literature focuses on both national policies that encourage international collaboration, and the effects of international collaboration in national economic outcomes. Chen et al. (2019) summarise the second line of thought, in relation to the positive effects seen to be associated with international co-authorship:

> Driven by increasing global competition and rapid technological changes, more and more countries have deemed the science and technology (S&T) collaboration across countries as a critical way to foster and maintain their global innovation competitiveness. A country with more collaborative linkages with other countries is placed in an advantageous position, which endows the country with privilege to leverage the domestic S&T capabilities and exploit the foreign investments in Research and Development (R&D). Thus, international research collaboration has been perceived as a dominant driving force for promoting S&T advancement, industrial innovation and economic growth (Chen et al., 2019, 149).

Numerous papers find that funding fosters international collaboration in science, while international collaboration in science facilitates access to equipment and funding (Birnholtz, 2007, 2233; Morillo, 2019; Muriithi et al., 2017), as if they are joined symbiotically. The growth of co-authorship in Europe and the inclusion of research cooperation in development aid packages (Woldegiyorgis et al., 2018, 167-168) both imply a positive relation between investment and internationalisation, though incentive effects vary at national level: 'while European agencies foster international collaboration through funding programmes, countries like the US tend to focus their funding internally, creating incentives for national collaboration' (Chinchilla-Rodriguez et al., 2019, 2). Collaboration enables time and resource economies, though the costs of coordination may increase at international level (Abramo et al., 2017, 1017-1018). However, the statistical relation between funding and collaboration varies by discipline (Morillo, 2019, 816).

An increasing number of countries 'have deemed the science and technology collaboration across countries as a critical way to foster and maintain their global innovation competitiveness' (Chen at al., 2019, 149). 'Inter-governmental S&T programmes [are] an important driving factor of international research collaboration' (160; see also Graf and Kalthaus, 2018; Katz and Ronda-Pupo, 2019). Cimini et al. (2016) find that the relation between international collaborations and scientific success is 'an open issue', but they still find it to be a 'fundamental parameter' (201, 210). Some university systems use financial and/or career incentives to encourage international and/or collaborative publication. This approach was widely used in China (Xu, 2020), though in early 2020 there was a change of policy: the national ministry de-emphasised the role of Web of Science papers in the evaluation of academic performance. Cross-border collaboration together with a national system willing to employ foreign researchers encourages the inward movement of foreign talent, providing that cross-border mobility is supported by migration policy. All else being equal such an open regime is likely to further encourage cross-border collaboration on an ongoing basis (Woldegiyorgis, et al., 2018, 164). Arguably the US, the UK, Canada, Australia and Switzerland have benefitted from policy structured openness in this respect.

The intrinsic difficulty with the science-as-national-innovation narrative is that science is not solely nation bound, as noted by *The Economist* (2021). Scientific knowledge enters a global pool. Some innovations in national industry must be sourced from outside national science; and at least some national science-based discoveries must 'leak' abroad, in that they are exploited by foreign industry for its capital accumulation rather than by national industry. There is a fundamental lack of alignment between global science and a single national economy. No national policy or narrative can squeeze the global system into the national container, like pushing toothpaste into the tube. Still, nations need scientific capacity if they are to access global science, and it is easier to justify spending on science with a claim about direct benefits. The national innovation narrative persists. It is the primary rationale for government funding of research in universities and other organisations and it partly orders the funding of disciplines, as well as the scholarship on science.

Some studies discuss national science in metaphors drawn from national economy. The ‘balance of knowledge flows’ model developed by Abramo et al. (2019) is derived from an analogy with the national balance of payments on foreign transactions; though the method is size biased (smaller countries produce less in volume and borrow more so using the measure, their science tends to be in deficit for that reason alone), and the analogy is dubious. Economic capital is zero sum, while shared knowledge is positive sum. National science benefits, in different ways, both when it gains new knowledge from abroad and when the knowledge that its scientists have generated is made use of in other countries. Other studies proceed further the inquiry into the relation between science and industry innovation, for example using patents as a proxy measure of innovation (Gazni and Ghaseminik, 2019). They find that the dependency of highly cited patents on science is more marked in the US and UK than Japan, South Korea, China and Taiwan in East Asia (1421). There is a larger variation between countries in the relation between highly innovative science and highly cited patents, than is the gap in science production (1423). Patelli et al. (2017) also use patenting as a proxy for innovation in industry, and map national scientific performance on the basis of global citations of both science and patents. Both sets of comparisons are modulated by cultural differences in regulation that are not acknowledged. Frenken et al. (2017) use Leiden ranking data on university-industry co-publication to indicate ‘innovation’ performance and not surprisingly find large universities, and technical universities, tend to ‘overperform’ (867-868). Only Switzerland does well in all three of citation impact, international collaboration and university-industry co-publication (868).

Papers that imagine science as a measurable part of the economy combine science as a generator of economic effects with the effects of economic investment in science. Cimini et al. (2016) find that scientific outputs grow with funding, though there is variation in the ‘national ability to transform financial input into bibliometric output’ (201). Using OECD data on investment in R&D, and Scopus outputs for 1996-2013, they identify a higher correlation between R&D spending and citation impact in the case of spending in higher education than spending in business (moderate correlation) or government research agencies (no evident correlation) (206-207). Docampo and Bessoule (2019) use a combined quantity and quality measure of scientific output to establish a ‘strong linear relationship’ between wealth and science output: outliers are Kenya’s science system that overperforms relative to wealth and Saudi Arabia’s that underperforms (1220-1221). They add that ‘it comes as no surprise that the research output of a country/state is by and large commensurate with its wealth; whether wealth is the scientific progress driver or the other way round is a debate’ (1221). Chinchilla-Rodriguez et al. (2019) find that for internationally collaborative papers, lead author position translates into citation gains when the country spends more on R&D as a proportion of GDP compared to spending in the partner countries – the relative economic factor correlates with relative scientific standing (9). Prathap (2017), using Google Scholar citations and GDP, establishes that at country level, not surprisingly, there is ‘a very strong correlation between nominal GDP and size-dependent research performance indicators’ (see also Bornmann et al., 2014). Piro (2019) examines the performance of institutions in obtaining European Framework programme grants in 2007-2017, devises Gini co-efficients for the distribution of grants within each country, and maps the concentration of R&D institutions in countries against OECD data on R&D as a share of GDP. High performing countries invest the most in R&D while exhibiting a ‘highly skewed R&D system’ in which a small number of institutions account for a high proportion of national performance (1095). Abramo and D’Angelo (2020) map ‘strengths and weaknesses at field level’ (1), focusing on the intensity of publication by top scientists in each field relative to expenditure on research (3). The stronger is performance using this indicator, the more that the field can be considered a national research strength (12). They confine their study to science in Italy.

In a challenge to the orthodox policy narrative, Klavans and Boyack (2017) argue that research is primarily driven by altruistic motives rather than economically-driven innovation. The researchers determine the character of research on the basis of disciplinary identity. They argue that while economic utility is dominant in parts of the applied physical sciences, such as engineering, and business management studies, these disciplines constitute a minority of papers in Scopus. Altruistic research includes curiosity-driven inquiry in all disciplines including the natural sciences and philosophical studies. 'Discovering basic principles of life and nature and making them manifest are an integral part of the human psyche' (7). To Klavans and Boyack fit is ironic that economically instrumental research secures far more attention than altruistic research. However, much of what they call altruistic research is not primarily driven by cognitive accumulation as an end in itself, it is designed to improve human life, society and/or the world. This includes most papers published in social science, law, education, ecology and medical science. The findings are not uniform across the world, however. In Russia and Eastern Europe, East Asia and Iran economically instrumental research outweighs altruistic research as they define it. There is scope for argument about some of the categorisation decisions made by Klavans and Boyack (2017), they miss altruistic research in national languages other than English outside the Scopus collection; they sidestep the indirect economic effects of altruistic research; and the term 'altruistic' is misleading for research designed to improve society but not the economy. Nevertheless, they demonstrate persuasively that motives related to capital accumulation in the economy are not nearly as dominant in science as the orthodox narrative suggests.

***Multilateral comparisons**.* Multilateral comparisons of national system performance in science are dogged by problems integral to all such exercises. When common indicators are used, performance is affected by factors that differ in terms of both inner and outer contexts. Countries have varying histories, resources and languages of use; and are variously positioned within the global system of relations. To what extent should these contextual differences be taken into account in standardising the comparison? To what extent *can* they be incorporated? The customary approach is to nod towards that problem and continue to pursue the comparisons as if each case is equivalent and it is hypothetically possible for any national system to excel in the same terms, within a single system of knowledge. A further problem, as noted, is that it is questionable when relational data such as indicators of co-authorship and citation are assigned arbitrarily and on a constant basis to single nations.

The early and influential multilateral comparisons of national performance in science by May (1997) and King (2004) focus on national economic efficiency. Working with papers from what is now WoS for 1981-1994, May (1997) argues that 'comparison of scientific output relative to government money spent on research and development (R&D) … is arguably the best measure of the cost-effectiveness of spending in support of basic and strategic research' (794). There are sharp variations between leading countries in citations per unit of expenditure. Nations in which research is concentrated in universities, rather than partly conducted in large public research agencies as in France and Germany, tend to perform better (796). May (1997) compares nations' share of total papers, papers per person, share of citations, citations per paper and per person; 'revealed comparative advantage' in each disciplinary field, meaning the fraction of a country's citations that are in that field relative to the fraction of the world's citations that are in that field, an indicator of not just performance but specialisation; and trends in the country share of major scientific prizes. The UK, Germany, US, Netherlands, Switzerland and France exhibit the most even 'patterns of scientific capability' (794). In papers and citations per person the strongest countries are Switzerland, Sweden, Israel and Denmark. May also notes in passing that 'the above comparisons are to a degree confounded because a large and growing fraction of scientific work involves international collaboration'; and 'there is an English language bias in the ISI [WoS] database, both in the journals included and in patterns of citation' (795).

King (2004) extends May (1997) to provide 'metrics for judging achievement' (311) and 'value for money' (315) across the leading 31 science countries. 'Achievement' is comprised by country shares of total papers, field normalised citations and top 1 per cent most highly cited papers. King compares citation intensity meaning citations per unit of GDP with wealth intensity measured as GDP per person. Smaller Northwestern European nations and the UK do well in citations per unit of wealth but there are no clear correlations among all wealthy countries. New PhD students as a proportion of the population measure each nation's 'knowledge base', and private sector investment in R&D in the public sector is presented as a proxy for 'the interaction and knowledge transfer between business and higher education' (314).

The primary economic measures of outputs are publications per researcher, citations per researcher, and citations per unit of investment on R&D in higher education (313 and 315). The UK leads the largest eight research countries on all measures. King, a UK government official in science and technology, notes that between 1980 and 1995 there was a considerable reduction in public spending on UK science, but this 'encouraged a level of resourcefulness among researchers, and approaches to industry and the EU that are now bearing fruit'. With public funding increasing again 'the pruned plant of UK science is regrowing vigorously' (316). King (2004) dismisses May's concern about language bias but has another concern. 'It is unlikely that these results reflect an anglophone bias, as it is now accepted that all high-quality papers are published in English. But anecdotal evidence suggests that preferential US citing of US papers may distort the analyses, given the sheer size of the US contribution (312). Less parochially, he focuses on global inequality in science, urging 'capacity-building between nations of high and low scientific intensity' (315).

May (1997) and King (2004) have had many later followers. Some, especially those generating reports within government, confine themselves to presenting the comparative data, inviting readers to interpret them as they wish (e.g. STO, 2019). Others look for explanations of national differences. Many different indicators can be used to calibrate nations in terms of 'quality' or 'performance'. Any indicator or combinations of indicators can be used to construct or suggest a causal argument. Once the principle of context-free comparison is installed, and its problems ignored, there is no end to the claims that can be created and expressed in universal terms. A succession of magic keys to national greatness flit across the scientometric landscape. However, no subsequent papers have dealt effectively with May's (1997) two qualifying points. Cimini et al. (2014), working with 1996-2012 Scopus data, 'use citation data of scientific articles produced by individual nations in different scientific domains to determine the structure and efficiency of national research systems', and their 'scientific fitness' or 'competitiveness'. They repeat May's qualifying points almost exactly, 17 years later – and again proffer no methodological solution:

> We remark that the results presented above are confounded to a certain extent because a large and growing fraction of scientific work involves international collaborations, and because of the English language bias in the Scopus database – both in the journals included and in patterns of citation. The latter observation could explain to a certain degree why anglophone nations like United States, United Kingdom and Canada do much better than, e.g., Germany, France, Italy, Japan and China (Cimini et al, 2014, 8).

Cimini et al. (2014) conclude that 'technological leading nations' are characterised not only by large volumes of papers and citations but also by the fact that 'they diversify as much as possible their research systems' (1). Lack of disciplinary diversity indicates 'under-development' along a normal path of research system evolution. This begins with the 'basic sciences', especially the physical sciences, and those 'more related to economic returns' such as engineering, and evolves later to include the 'sophisticated domains' of the medical sciences, social sciences and humanities called up by 'a complex social and economic substrate' (8-9). This does not resolve the question of causality: does the success of leading nations derive from disciplinary diversification of 'competitiveness', or does success enable diversification? Or are the indicators uncoupled? Abramo and Angelo (2020) review the literature on 'the scientific standing of nations'. Comparisons by Bornmann et al. (2014), Patelli et al. (2017), Prathap (2017) and Gazni and Guaesminck (2019) are mentioned above. Most comparisons focus on indicators typical of Euro-American practice, rather than, say, East Asia, Russia, India or Iran; for example in relation to the disciplinary mix and the role of university science in industry innovation. Comparisons are also used to ask more specific questions than holistic assessment of performance. Gringas and Khelfaoui (2018) consider the extent to which nations collaborate with US science and derive a measurable citation advantage in doing so. Packalen (2019) compares each nation's recency of citations in papers in biomedicine, with recency held to indicate 'novel science'. He finds that 'countries continue to differ in their ability to take advantage of cutting-edge ideas' (806), though 'the results do not reveal the specific mechanisms driving these differences' (804).

In the comparative process countries are calibrated using single indicators such citation rates and the proportion of papers that entail international collaboration, and there is rarely much discussion of how contextual elements affect the outcomes of comparison. For example, Shashnov and Kotsemir (2018) provide extensive data on scientific output and collaboration in the BRICS countries, and identify areas of weakness in each country suggested by the comparison data, but in contextual terms provides only basic data on resources and little that could assist explanations. When comparative data are left to stand on their own this merely invites unsecured explanations. However, the studies by Chinchilla-Rodriguez and colleagues, discussed below, attempt a partial contextualisation of the countries compared, for example by articulating comparison through differences in national investment in R&D. Cimini et al. (2016) likewise interpret the data on outputs, citation and collaboration in terms of differing investments. Choi (2012) tests indicators of GDP per head, geographic region, language of use, broadband penetration and student mobility (the last two seen as indicators of 'globalisation') against national collaboration patterns. There is a weak correlation with geographic and linguistic factors; no statistically significant relationship between GDP per head and co-authorship; and no positive relation between Internet penetration and co-authorship. However, student mobility between countries is positively correlated with co-authorship (31-33). This kind of work may be the beginning of a more nuanced approach to the study of and comparison of national science systems.

A significant part of the literature compares national system performance in fostering cross-border scientific collaboration, which, as noted, is treated as a universal virtue. These comparisons are complicated by the statistical effects of differing conjunctions of size and growth. During rapid development larger emerging nations may significantly increase cross-border papers and yet exhibit slow growth or no growth in the internationally collaborative share (Barrios et al., 2019, 639). All else being equal, smaller countries, whether emerging or established, tend to have higher international collaboration ratios than do larger countries, though patterns are more mixed in Europe (Kwiek, 2020, 7). The orthodox explanation of this pattern is that smaller systems lack absolute capacity. Large systems have multiple potential internal partners and a larger potential for national division of labour. If small national science systems want to connect effectively in all fields they cannot provide everything at home and must search for complementary capabilities outside national borders, or so the reasoning goes (Barrios et al., 2019, 633; NSB, 2018, 122). Frenken (2002) and Frenken et al. (2009) note that if scientists chose their partners randomly, large national systems would have relatively high rates of domestic collaboration, and small systems would be overwhelmingly internationalised, more so if neighbours were geographically proximate. But when the comparison between actual and random distribution of partners is made, ‘countries with most researchers actually display the weakest bias to collaborate domestically’ (Frenken et al. 2009, 224). This includes Germany, France and the UK in Europe, and the US. Given this, the 39.2 per cent rate of international collaboration of US papers in 2018 indicates an exceptionally high level of engagement that signifies the centrality of US scientists in the global science system. Yet whichever way the relation is understood, the propensity to collaborate internationally is nuanced: it is not a uniform function, it is not determined solely by factors intrinsic the science, and system size is not the only factor in play. Disciplinary, geographical, cultural and geo-political factors also matter; and nation-states deliberately pursue varied trajectories of development.

***The nation as node.*** Network analyses are capable of fine-grained investigation of individual disciplinary links, relations between cities and ties between institutions across the world. It is strange that they are employed on the basis of individual nations as the node. This level of aggregation not only conceals a complex of internal and external relations, it is of questionable relevance. The nation-state has an identifiable legal, territorial and political authority. But it is not the nation-state that determines network diagrams, it is a junction of scientific co-authorships which bear national identifiers. The junction labelled ‘nation’ does not operate as a bounded entity in scientific networks. It does not determine the formation of new edges or the cessation of existing ones, which are shaped by many different decisions made on a cross-country and decentralised basis. In what sense then can it be considered as a single node? The nation as node is a fiction. Nevertheless, it is a convenient fiction: it enables network analysis to combine global data with methodological nationalism, coupling the global science system with national presences and interests.

The idea of nation as node is so pervasive that it is used by some researchers for whom global science is primarily understood as autonomous network, as a shorthand method of mapping collaborative relations in the whole of science at world level (e.g. Leydesdorff and Wagner, 2008; Wagner et al., 2015). Wagner et al. (2017) focus on disciplinary networks but also interpret them on the basis of nation as node (1637). Choi (2012) 'defines international scientific collaboration as a co-authorship relation between countries' (26). The study uses Web of Science data for 1995-2010 and focuses on the 30 countries that were members of the OECD throughout the period. It establishes that in 2010 there were 431 of a possible 435 'ties' between national nodes in the network, though these individual 'ties' contained a very large variation in the number of co-author edges. Nations are compared in terms of degree centrality, which measures the number of connections into other national science systems. At this level of aggregation degree centrality is a blunt tool. Chen and Chen (2015) study the characteristics of the leading one hundred science countries, ordering them in terms of 12 groupings based on specialisation, volume and impact. Zhang et al. (2018) use social network analysis to examine the centrality of the world's largest science systems, in their case 40 nations, in terms of Web of Science output between 2000 and 2015. Barrios et al. (2019) map international collaboration on a country basis using international co-publication data for 1997-2012 from the US National Science Foundation, and focus on patterns of convergence in collaboration between nations as super nodes. Frenken (2002) and Franken et al (2009) also work with the nation as a single entity, comparing actual inter-national activity to randomly distributed links and thereby identifying spatial biases at country level in collaboration, citations and mobility. Kato and Ando (2017) map cross-national science collaboration against the cross-national mobility of researchers, and also variations in national resources. Lee and Haupt (2020) map cross-national collaborations in relation to Covid-19 in 2020 against cross-national collaborations in all science in 2015-2020. Piro (2019) reworks institutional data on performance as an investigation of stratification in national systems. All these studies treat nation as a primary category in investigating data collections, and explaining relations, that are at least partly disciplinary and global in form.

***The nation alone.*** In the final stage of this methodological journey, from global science in its proxy form as bibliometric data into the nation as its own boundary, scientometrics moves from the nation as node to the nation alone. Numerous studies use extracted bibliometric data to investigate single national science systems. Some seek to derive larger generalisations from nation-only data, an approach which characterises successive papers by Abramo and colleagues, who work largely with bibliometric data for Italy alone.

Many nation-only studies focus on the nation's position within global science. For example, Avanesovsa and Shamliyan (2018) review the 'research performance of Russian institutions' in comparison with those of other nations, using data from web of Science, Scopus and SciVal and national Russian data bases. They investigate paper volumes, citations and high citation papers, and collaboration patterns, relative to population and GDP. They emphasise comparisons between Russia and the US. The overall summation is that Russian science performs poorly in comparative terms, though one reason is that Russian researchers are not sufficiently encouraged to publish in English, which if redressed would secure greater global recognition for the nation (2035). Institution by institution data show that Russia has centres of exceptionally high performance in research in physics and astrophysics and that most national research organisations with the highest global citations are part of the Academy of Sciences. Basu et al. (2018) tackle the question 'does China already lead world science' using paper volumes, citations, number of researchers, and high technology manufacturing and exports. They also examine review reports on specific sectors of science. Again, they emphasise the comparison with the US. The answer to the question is that it depends on the metrics used, and the disciplines in the comparison, but the US is likely to retain world leadership for the next twenty years at least (267). Other researchers also explore aspects of comparative performance in China. Zhou and Glanzel (2010) use Web of science data for 1997-2007 to investigate China's comparative role in internationally collaborative papers, noting that growth of total papers had outstripped growth of internationally co-authored papers, and that almost half the collaborative papers originated from Beijing, Shanghai or Hong Kong (610). Zhou and Bornmann (2015) use Web of Science data from 1980-2010 to compare the science systems of China and Germany, and discipline-based collaborations between the countries. Overall, collaboration with German colleagues tends to enhance the global citations of papers with Chinese authors. Quan et al. (2019) use Web of Science data for 1980-2016 to investigate the relation between first authorship, team size and citation impact. While average team size and the leadership role of Chinese scientists had advanced, on average Chinese led papers were associated with smaller teams and lower citation impact than was the case with China-follower papers (718-719).

Other nation-only studies ask more bounded questions. Kwiek (2018) investigates the characteristics of high achieving researchers by analysing bibliometric and survey data drawn solely from Poland. He finds a highly skewed pattern in which advanced productivity is concentrated in a small minority of performers, in this regard replicating other national studies (445). Interestingly, in Poland career success and high productivity are decoupled (448). This appears partly true also in Italy but may not hold for all national systems. Jeong et al. (2011) used detailed local data on publications and research biographies over 1997-2010 to investigate factors that condition research collaboration in a single research organisation in Korea, the Korean Institute of Machinery and Materials. Hu et al. (2018) trace the engagement of UK science in Europe and the possible effects of Brexit for science, technology and innovation in both the UK and other European countries. Winkler et al. (2015) map the diffusion of the Internet against domestic and international collaborations by American scientists in 1200 scientific institutions. Agrawal et al. (2019) find that foreign trained scientists working in the US science system have a citation impact at least as strong as that of locally trained scientists, though only after they begin working inside the US. The fact that 'better-connected' US trained scientists do not enjoy a citation advantage suggests that no harm is done to US science by employing foreigners (10-11). Anh et al. (2019) investigate the networked relations of Korean universities with each other and with 'the international research community'. They identify a group of 'bridging universities' that link second tier Korean universities with the global science system (p. 519). This is a rare study which combines network analysis tools with a sharp sense of hierarchy within the national system and keeps all of the local-institutional, national and global scales in view.

## Scale as materiality: The global system

As indicated by the data provided above, the size of the global science system has greatly increased in terms of both the pool of knowledge and the number of active authors, the system has become more interconnected in terms of both knowledge flows and networks between people, and the number of science active countries has greatly increased. Despite the limitations of most orthodox scientometric studies, generated not by the bibliometric data per se as by the normative and universalising frameworks used to interpret it, especially methodological nationalism, the literature on science provide many insights into the materiality of global science. Even methodologically nationalist studies contribute illuminating data despite the reductionist framing. Other studies work more freely with the global scale and bring its materiality into fuller view. Studies of science in scientometrics and other literatures, in conjunction with theorisations of networked social relations, can illuminate the global science system in two ways. First, in terms of the dynamics of the system/network as a whole, at the singular level of system. Second, in terms of the factors external and internal to the work of individual scientists that govern their activity and especially their networked relations with each other. The latter includes research specifically focused on those networked relations, including studies of citation patterns and the voluminous literature on the co-authorship of papers.

At the outset limitations of these various global studies should be kept in mind. Networked-based analyses foreground certain elements and occlude others, though the partial character of their coverage is rarely acknowledged amid the typical claims to universality (typical not just of this field but of much of mainstream quantitative social science). First, as noted, the conventional treatment of bibliometric data is unable to adequately encompass national science, being constrained by the global character of those data, but in seeking to identify national science it stymies the understanding of the global system qua system. Being derived from the bibliometric data bases global science excludes almost all papers and other knowledge-based communications in languages other than English, including endogenous knowledge (Marginson and Xu, 2021). By definition, this omission is not apparent in the bibliometric collections and it is only rarely discussed in science studies, though it is recognised in the literature in development studies and related fields (e.g. Connell, 2014; Mills, 2020). However, again as noted, many if not most scientometric and other studies of science want to encompass the national scale and compare one nation with another. They habitually assume that each national slice of the global relational data can provide a valid picture of national science. There is a disjunction between the normative and empirical frames. Only a minority of studies working with global bibliometrics norm science as global. These are network studies that conceive science, either in all disciplines or in selected disciplines or topic areas, as a single space (e.g. Jeon, 2003; Wagner and Leydesdorff, 2005; Cabanac et al., 2015; Abbasi et al., 2018; Berge et al. 2018; Bravo et al. 2018; Citron and Way, 2018; Zhou et al., 2018; Larregue et al. 2020). Some such studies are discussed further below.

In a further group of studies by Chinchilla-Rodriguez and colleagues, associated with world systems theory (Marginson and Xu, 2021), and discussed at the end of this section, the researchers attempt to isolate the conditions of national agency within the global scale. Though these papers are only partly successful, they take forward the understanding of relations of power within global science.

Second, the strength of network-based models is that they capture something of the expansionary dynamism and openness of scientific relations in the unregulated global scale. Yet network analyses have a prima facie tendency to emphasise horizontality and openness. They focus on connections rather than on gaps in actual or possible relations, or on vertical relations of domination. Network studies generate pictures of unimpeded flows and nodes that connect at the same time everywhere within a common system of relations. In reality there are breaks and blockages in potential linkages; and multiple sets of connections for each node rather than the one single interconnected system implied by network diagrams regardless of internal differentiation. There are also occlusions in network diagrams: phenomena showing as nodes and edges appear as equivalent, interchangeable. Heterogeneity and ambiguity are lost. For example, in the real world some links embody mutuality while other embody one-way influence. In scientometrics there is interest in inequalities, for example in Chinchilla-Rodriguez et al. (2018a) and Chinchilla-Rodriguez et al.

(2019), but the quantitative analyses used in the field leave the hierarchies inside networks under-explained and fail to encompass the external relations of power in which scientific networks are situated. Network analyses include concentration measures such as degree centrality but network-based centrality (Scott, 2017) is a limited proxy and bland descriptor for the structural compulsions of a social hierarchy. Global science is structured by hegemonic relations of power in which capacity and output in science is increasingly plural at world level but English language and Euro-American practices are dominant. The leading Anglo-American systems and universities, especially those in the US, exercise a larger geo-political and cultural role than is captured by quantitative measures of comparative outputs, co-authorship or citation flows (Marginson and Xu, 2021).

**Global structure and dynamics**

In *The Network Society* (2000) Castells explains the developmental logic of networks. As the network grows each successive node is added at negligible cost. It adds value to the existing nodes by increasing the potentially fruitful connections and cheapening the average unit cost of each connection across the network. Networks continually call new agents into being, expanding naturally towards complete inclusion of every possible node, while at the same time adding every possible connection ('edge') between existing nodes. Because the global science system is a communications network it tends to expand freely in the manner that knowledge itself spreads, with an almost liquid fluency. The rapid growth of globally connected science evidenced in the data on paper output, growth in the countries in which citizen scientists are active, the burgeoning citation flows and the growth in the number and proportion of co-authored papers, all evidence this expansionary dynamic. Studies of networked collaboration based on distance, rather than nationality or institutional identity, register a continuous increase. Waltman et al. (2011) examine 21.4 million WoS papers for 1980 to 2009. The average collaboration distance per publication rose from 334 to 1553 kms. Between 2000-2009 alone the average collaboration distance increased by 3.4 per cent a year. 'Despite significant differences in globalisation rates across countries and fields of science, we observe a pervasive process in motion, moving towards a truly interconnected global science system' (Waltman et al. 2011, 574). Tijssen et al. (2012), working with 11.1 million WoS papers for the 2000-2010 period, establish an annual increase in average collaboration distance of 5.2 per cent. At the same time the average intra-country collaboration declined slightly. Geographical expansion was concentrated in the global system (5). Wong (2019) also notes the quantitative expansion in global networking.

Network growth combines this extensive expansionary dynamic with an intensive concentration dynamic. Crucially, these two processes are not necessarily zero-sum. Networks encourage the continual expansion of connections while facilitating *both* 'flat' horizontal relationships and concentrations of network power, exemplifying Castells's (2001) theorisation that the Internet 'allows metropolitan concentration and global networking to proceed simultaneously'. Networks cluster at primary nodes, empowering those nodes, while spreading inclusion. Outward expansion has been so rapid that Wagner et al., (2015) find that it is larger than the tendency to concentration. Not all studies agree. Network analyses seek a summative resolution, greater concentration or greater dispersion; but because both tendencies are always in operation, the different analyses seem to oscillate in an unstable manner between empirical findings of growing concentration or growing dispersion. It depends exactly what is measured, and how, and over which time frame: a change in methodology can be sufficient to tip the balance one way or the other.

Hence on one hand Wagner and Leydesdorff (2005), Wagner et al. (2015) and Wagner et al. (2017) find in favour of growing dispersion. Wagner et al. (2015) find that the number of countries in the 'dense centre of the network' was 35 in 1990, 64 in 2005 and 114 in 2011, and the periphery of the network is relatively open. 'Most nations have scientists who are participating actively in international collaborative networks', and 'new entrants are able to find collaborators without having to pass first through a core of highly powerful (or central) nodes'. The network does not fully mirror the structural logic of global inequalities (6). Wagner et al. (2017) report that 'power is not concentrating in a few large nodes' (1640). 'By 2013, the United States is no longer as "between" other nations as it was in 1990. Likewise, there were low levels of 'clustering'; 'cliques are not growing rapidly'. The overall picture is one of 'a denser, more connected, and more equitable network' (1642) in which scientists from emerging national systems freely connect across the decentralised global system, including with each other. On the other hand, Leydesdorff and Wagner (2008) find consolidation of the intensively linked inner group of countries, which shrank from 22 in 1990 to 14 in 2005, while 'countries at the periphery may be disadvantaged by the increased strength of the core' (317). Perhaps the instruments of network analysis are more zero-sum than is networked global science: hence the instability in empirical findings. One or another tendency may be stronger in different times or disciplines; or in relation to the measures; but there is no equilibrium in relations between diffusion and concentration; no final settlement in the antinomy of horizontality and hierarchy. Both are inevitable. 'An analogy could be drawn to a volcano where the base is getting wider, but as it grows, it pushes the summit at the centre higher and steeper' (Leydesdorff and Wagner, 2008, 321).

Other studies suggest the same oscillation between extension and concentration, including Graf and Kalthaus (2018) and Abbasi et al. (2018). In their work on the global photovoltaics knowledge network, Graf and Kalthaus (2018) identify 'an exponential increase in network size' (p. 7) and horizontal extension. There is an increase in the average degree of national systems, to the extent that on average the actual connections as a share of all possible connections are rising, 'The network becomes increasingly interconnected, suggesting that the global system functions well and allows for knowledge diffusion. However, there seems to be an ongoing centralization process, such that some countries form a highly inter-connected core, which is also been found for other fields' (Graf and Kalthaus, 2018, p. 12). The researchers examine the evolution of global network structure in overlapping time periods between 1980 and 2015 and find that network density has increased despite network growth, while betweenness centralization, the extent to which particular central national systems mediate system relations as a whole, increased in the early periods and diminished later (pp. 5-6). Abbasi et al. (2018) find that agents who bridge to otherwise unconnected nodes have stronger measured performance than those whose connections are narrower, intensive in a localised group (587-588); though the measures of performance include citation volume, which all else being equal tends to be augmented by an expansionary strategy. Berge et al. (2018)

continue this line of thought, moving beyond the alleged trade-off between extension and concentration with their notion of ‘bridging centrality’. Whereas the standard notion of ‘network centrality’ (see also Zhou et al., 2018) refers to multiple connections, ‘bridging centrality’ emphasises linkages between nodes that are otherwise poorly connected, creating more diverse combinations. A high number of bridging paths implies a more open position in the network and suggests ‘access to a more diversified knowledge pool’, which in turn suggests that ‘knowledge flowing through bridging paths is more likely heterogenous and non-redundant’, broadening the scope of actors to generate innovations (1034). Bridging paths track the concentration of dispersion, a notion that combines Castells’s two inherent properties of network growth.

Global science is less a single network than a combination of many different networks that embody conversations within and across disciplines. Arguably, studies at discipline and topic level can achieve a closer purchase on system dynamics. There are variations between disciplines in rates of citation, the size of author groups, and the proportion of papers with international teams (Winkler et al. 2015, 129-130; Barrios et al. 2019). Where there are formal programmes for collaboration, where equipment is shared (e.g. telescopes, synchrotrons) or the subject matter is intrinsically global (e.g. climate change, water management, energy, epidemic disease) the intensity of collaboration rises. Finklestein et al. (2013) state that faculty working in disciplines that entail empirical observation and quantitative analysis were more likely to collaborate internationally, perhaps because they valued data sharing (337). Klavans and Boyack (2017) find that in disciplines in which the involvement of industry is relatively high the proportion of articles with international co-authors is lower (17). Correspondingly, basic science is more internationally inclined than applied science (Woldegiyorgis et al. 2018, 167), though the difference between the two domains is shrinking (Barrios et al. 2019, 634-635 and 644-645). The proportion of papers with international co-authors is relatively high in the natural sciences. In 2016, cross-border authorship was 54.0 per cent of all papers in astronomy and over 20 per cent in the geosciences, biological sciences, mathematics, physics and chemistry, though lower in medical and health sciences (see also Gazni et al. 2012, 324), the professional discipline of engineering and in social sciences, where subject matter is more often national or local than is the case in natural sciences. Nevertheless, between 2006 and 2016 the international share rose in all disciplines, including from 13.7 to 17.7 per cent of papers in engineering and 11.4 to 15.4 per cent in social sciences (NSB, 2018, 122; Graf and Kalthaus, 2018, 2).

Amidst these differences Wagner et al. (2017) find similar structural forms in six different disciplinary networks. 'The specialities have taken on properties related to networked communications, rather than unique properties of epistemic cultures' (1646). Except in mathematical logic, where there are fewer authors, between 2008 and 2013 all disciplines registered rapid growth in the number of national systems intensively engaged in the global network, and in the connections between them. In some but not all disciplines network density had increased, meaning growth in the proportion of potential edges actually realised (1636-43), and there was a great growth in new agents from existing and additional science countries (1642). Again, the pattern is network intensification combined with network extension, openness and some diffusion of scientific power. In their study of the evolution of co-authorship networks Citron and Way (2018) likewise establish similar patterns across fields. They focus on four topic areas, quantum computing, magnetic material properties, transport measurements, and mechanical properties of materials, using an open-access repository of 189,000 pre-prints titled arXiv, covering 1992 to 2015. Previous studies have shown that in different fields 'each co-authorship network undergoes a topological transition in which a densely connected giant component of researchers forms over time' (182). This normally occurs in three stages. First, 'each network begins as a disjointed set of cliques, as the authors who share a field publish in separate groups. Next, a few of the cliques join together, forming a loosely connected, almost tree-like backbone of connected cliques. In the final stage, enough cliques overlap with one another such that the largest connected component becomes densely connected' (184). There are multiple collaborations between whole research groups. However, the third stage was reached only in quantum computing, and magnetic material properties; it was reached in 22 of the 50 topic areas investigated in the full study (186). Citron and Way (2018) remark that collaborative networks require 'significant efforts to maintain' and do not always survive in perpetuity. If edges lapsed after a few years, this significantly slowed growth of the giant components or prevented them from forming; though in quantum computing, and magnetic material properties, lost edges were usually replaced (187). This underlines the notional character of many scientometric network diagrams, which capture the accumulated history of edges in the network, not the ongoing connections. In their study of long term publishing patterns in computer science Cabanac et al (2015) make a related point: more than two thirds of co-authorships were one-off and fail to generate ongoing collaborations (147).

Larregue et al. (2020) provide a discipline-specific study of global epigenetics using 1991-2007 WoS data. The focus is on individual-level collaborations, with individuals primarily categorised in terms of institutions. This study uses keywords to map 'the development and structure of the epigenetics field' by tracing epistemological paths, connections and breaks. The authors trace the largest institutional producers by location, the main sub-disciplinary specialisations (8-10), and changing patterns of collaboration on the basis of institutions and individuals, identifying overlapping 'sub-communities' (11-14). They distinguish between the conceptual apparatuses used by researchers, diversity of field identity, and their thematic interests, diversity of topic of inquiry (17). They find that over time the intellectual structure of the field has become more heterogeneous and different networks have become increasingly autonomous (pp. 1-2, p. 22). Larregue et al. (2020) note the contribution of the research is also its main limitation: the macro-level quantitative approach means 'we might here and there lack some analytical depth and nuance'. They suggest qualitative interviews and fine-grained investigations of content themes (p. 23). This is a useful indication of the potential and limits of scientometric network analysis.

**Collaboration in the autonomous network**

In their successive studies Leydesdorff, Wagner and colleagues note that the global science system is bottom-up and self-evolving. This draws attention to two salient characteristics. First, the networked global system is autonomous vis a vis national and international organisations, including both states and economic capital. In relation to capital accumulation, the large publishing companies sustain the calibrated journal hierarchy and may encourage the continuous expansion in the volume of papers, but they do not shape the contents of science. Second, the networked global system is grounded in the autonomous agency of individual scientists and their freely evolving relations with each other, especially across borders. Scientists are not wage labourers but autonomous creators, though their scope for agency is variable, being mediated by discipline, country, institution, professional norms, seniority, perhaps individual characteristics such as gender and ethnicity, and in most cases, success in a building funding base for their work. Arguably, in its inner culture the self-regulating scientific network is closest to the life of research-oriented faculty universities in the US. This is unsurprising given that US faculty played the main foundational role in the early 1990s roll-out of Internet communications in science.

Many of the relations between individual scientists are modest in scale and may not be specifically funded, simply resting on donated time within open communications networks. Wagner et al. (2017) note that global cooperation is not just driven by 'big science', large projects with multilateral budgets. 'Many "small science" projects at the international level are based upon the shared interests of otherwise unrelated parties, working independently of organizing imperatives or shared resources, to find reasons to cooperate despite geographic distance' (1634). The 'spectacular growth of international collaborations may be due more to the dynamics created by the self-interests of individual scientists rather than to other structural, institutional or policy-related factors' (1616). Likewise, King (2011) describes the global system as 'a largely privately governed network' (359). It is an individualised matter 'largely outside the control of governmental authorities' that constitutes 'a move from scientific nationalism for most researchers' (360-61). The global system is 'develops unpredictably on the basis of free individual exchanges' (372). It is always becoming, 'a constantly emergent social system' regulated by 'standards that help constitute and coordinate scientific practices worldwide' (362). These standards, common across science while also culturally specific and framed by dominant countries and organisations, include language and notions of 'autonomy, objectivity, testability, and peer judgment' (371).

Notwithstanding the dynamism of extension and intensification, scientific networks do not expand themselves. The growth of the global science system and constituent networks is above all sustained by the commitments of scientists and their drive to collaborate and produce. A large literature bears on explanations of, and motivations for, collaboration. Nationally bordered collaborations outweigh international collaborations by almost two to one, but the overwhelming focus of studies of science is on factors affecting international collaboration and the effects arising from it, perhaps because bibliometric data foreground cross-border collaborations and encourage the pervasive normative globalism.

Georghiou (1998) provides an early discussion of factors affecting collaboration. Chen et al. (2019) and Woldegiyorgis at al. (2018) present comprehensive overviews. Chen et al. (2019) review the 1957-2015 literature on international research collaboration, identifying five primary areas of research investigation: drivers of international research collaboration, patterns in collaboration, effects of collaboration, networks in collaboration, and measurement of collaboration. Explanations of collaboration are summarised as political, economic, cognitive, spatial and social (161). Many studies focus on the impacts associated with international collaboration, including the research performance of national systems. Woldegiyorgis at al. (2018) summarise the activity rather than research on it, listing national, institutional and individual ‘rationales’ or norms of collaboration, and noting among the conditioning factors international graduate mobility, the global character of knowledge in the sciences, funding, regional Europe and the policies of multilateral grant agencies. Many studies touch on specific causes or conditions of collaboration.

Studies focus on a mix of intrinsic and extrinsic factors, and the interactions between them; for example, the mediating effects of funding on motivation. The larger emphasis is on intrinsic factors. In relation to extrinsic factors affecting collaboration, Winkler et al. (2015) note the expansion of electronic connectivity, the growing mobility of scientists, growth in international doctoral studies, the growing importance of interdisciplinary research, funding designed to foster collaboration and the increasing role of large equipment in discovery, necessitating cross-border sharing of resources (116-121). Kato and Ando (2016) note the diversification of research capacity across the world, the advance of global communications and travel, greater researcher mobility, in association with the 'self-organising network structure' of science (675). It is in the sphere of extrinsic factors that national and institutional policies and strategies maximise their influence on the pattern of global science. Governments invest in science to secure competitive advantage, or to close the gap with those countries that have it (Chinchilla-Rodriguez et al. (2019, 1), and the values and priorities they bring to bear on science can shape what it does. The 'autonomy of science is mostly limited by the need to obtain funding and by the agendas of the organisations and nations that provide it' (Chinchilla-Rodriguez et al., 2018a, 1486). Studies note variations between disciplines and between national systems in the external factors at work. Muriithi et al. (2017, 2) suggest that in Kenya the balance between collaboration driven by the intrinsic interests of scientists and collaboration driven by funding is tilted more towards the latter than is the case in resource-strong national systems.

There are also studies that suggest that extrinsic factors are modified or supplemented by intrinsic factors. Melin's (2000) small survey of 195 scientists in Sweden, supported by seven interviews, finds that 'collaborations are characterised by strong pragmatism and a high degree of self-organisation' (31). The expressed primary reasons for collaboration were the knowledge and/or resources that partners provide, followed by social factors such as long-standing friendship, or a supervisor-student relation (34). 'Personal chemistry, respect, trust and joy are words that come up in the interviews' (36). Almost all respondents emphasised the importance of networks as mediums of collaboration (35). Schott (1998) focuses on the junction between cognitive accumulation and social ties between scientists, within the framework of shared professional norms and conventions (115), noting that the elements of commonality are especially necessary to the explanation of ties across borders. The survey by Ryan (2014) in UK finds that among research scientists intrinsic agential factors such as 'internal self-concept motivation' are strongest and instrumental motivations are weakest, confirming previous studies that emphasise intrinsic factors (356-357). 'External self-concept motivation' triggered by valuation by others is higher among young scientists than others (362). Here 'internal self-concept motivation' is a relatively broad category which takes in all of self-esteem, curiosity and intrinsic commitment to knowledge. Finkelstein et al. (2013) find that in institutions where faculty drove internationalisation the odds of collaborating with international colleagues in research were nearly twice as great as in institutions in which international activity was administratively driven. Abramo et al. (2017, 1017-1018) refer to the gains international collaboration offers in terms of all of skills and knowledge, time and infrastructure and resources, the reduction in isolation and the obligations of group membership, and individual reputational gains. Kato and Ando (2016) foreground the intellectual and social motivations of scientists, that are facilitated by processes of globalisation (676). Their own study, using metadata from papers published in *Nature* and *Science* in 1989-2009, finds that 'the researchers' intrinsic motivation and their international migration explain international collaboration' (691).

In forming partnerships scientists are motivated by both similarity and difference in relation to the partner. 'Political, linguistic, historical, geographic, and cultural proximities have been identified as drivers of international collaboration across countries' (Barrios et al. 2019, 633; Chen at al. 2019; Chinchilla-Rodriguez et al. 2019; Graf and Kalthaus, 2018, 3; Kato and Ando, 2017, 691; Maisonobe et al. 2016, 1026). It is often asserted that geographic adjacency encourages collaboration (Frenken et al., 2002, 356; Frenken et al., 2009, 224) especially when researchers share a land border. Physical proximity – whether within countries or in closely adjacent countries, for example those enabling travel within the same day – sustains organic forms of cooperation, whereby people meet in the same location and friendships can form. Hennemann et al. (2012) find that in the case of electronically-mediated cooperation, distance is not determining, but when the geographical gap is modest then the various kinds of proximity matter. Most studies find that in addition to immediate geographical proximity, all else being equal, scientists tend to cooperate with those with whom they share language and tradition and/or those who are located in countries of historical affinity. Often, as in Latin America, Arabic-speaking countries, Nordic and the German speaking systems, and in East Asia, the geographical and cultural-linguistic proximities coincide. Data on co-authorship patterns by country indicate strong biases between scientists in these groups. For example, scientists in the Nordic countries partner each other at between 3.03 times (Denmark-Finland) and 4.54 times (Sweden-Finland and Denmark-Norway) than they would be expected to do on the basis of collaboration patterns with all countries (NSB, Table S5A-34). Chinchilla-Rodriguez et al. (2018a) highlight regional collaboration in Latin America (p. 1497). Barrios et al. (2019) identify regional patterns. However, when there are severe political barriers proximate collaboration is retarded, as in the case of India and Pakistan. Former colonial ties often encourage potential collaboration, regardless of geographic separation, as in the Anglophone and Francophone worlds, though the opposite effect, post-colonial rejection, is also possible. Another kind of proximity is felt by diasporic scientists who retain contact with the homeland, for example Chinese postdoctoral scholars in the US, or diasporic scientists work who with each other. Note, however, that Choi (2012) reaches a contrasting conclusion, stating that: 'geographical, linguistic and economic affinities did not have a substantial impact of the formation of co-authorship network between "advanced" nations, different from previous research results' (25). Geography and language were statistically significant factors but at a low level (32).

Distance and difference are alternate motivators to proximity and similarity. Georgiou (1998) and Melin (2000) note that widespread desires for collaboration across borders predated formal programmes designed to build such collaborations such as European funding schemes. In such cases 'very often, there has to be a personal chemistry at play … sometimes even friendship' (Melin, 2000, 39); but some studies refer to intrinsic motivations of researchers to work internationally that are separable from cognitive, financial, career-positional, status, national or institutional drivers (e.g. Ryan, 2014, 357; Maisonobe et al. 2016; Kato and Ando, 2017). Melin's 'friendship' is often cross-cultural, which all else equal requires more effort than same-language/culture local friendships and so rests on sufficient personal drive. Schott (1998) refers to the subjective stance of 'outwardness' (p. 134) – though as Helibron (2014) notes, this can be accompanied by disciplinary closure (695). International collaboration is less likely than is local collaboration to be cross-disciplinary (Wuesterman et al., 2019). In their study of one research institute in South Korea, Jeong et al. (2011) state that 'most kinds of collaboration begin informally and are often the result of an informal conversation' (971). They find widespread intrinsic desires to work with others, noting that 'researchers with superior academic records prefer collaboration to sole research' (979). Whereas national links have the potential to infringe on time for international collaboration, the converse is not the case: the shorter duration of international travel means it does not infringe on potential national and local collaborations.

As the above account shows, the literature on science offers a long list of conditions and motivating factors affecting collaboration between scientists, without always clearly distinguishing between them, or theorising or modelling their interactions in a definitive way. However, there are two primary explanations that are offered for collaboration, which can be called cognitive accumulation and preferential attachment respectively.

***Cognitive accumulation.*** The collaborative activities of human agents are always quickened by common knowledge, but more so when knowledge itself is the stock in trade. Scientific knowledge grows like a language and transfers with the speed of all information. Given that knowledge is the essential matter that comprises science, it can be argued that cognitive accumulation has been underestimated in the literature on collaboration. By cognitive accumulation is meant the processes whereby scientists working to the larger pool of knowledge and activity, build ideas, data and novel theorisations. Knowledge formation is always the outcome of direct and indirect collective processes. Each person's new ideas rest on accumulation of the work of many others, past and present. Though much is achieved by individuals working alone against the backdrop of past knowledge, other knowledge grows when pushing forward together either synchronously or asynchronously. Collaboration can overcome individual isolation; bring potential extensions and complementarities into view; expand and diversify the opportunities for learning and new insights, joint and individual; builds critical intellectual mass; enables a larger division of labour; and augments the communication and promotion of the work. Simply put, 'researchers who collaborate … do not just add their individual expertise for a joint output but also exchange information and learn from each other' (Graf and Kalthaus, 2018, 2). Collaboration is especially facilitated by prior cognitive agreement (Birnholtz, 2007, p. 2234; Frenken et al. 2009, p. 230) but can also contribute to cognitive strengthening and cross-disciplinary fertilisation. The quality or excellence of a research group is motivating. So is the availability and communicability of scarce cognitive or information resources such as knowhow, research samples and data.

Cognitive factors are best understood in studies at the level of disciplines and below. Factors in play at the level of the individual in the discipline include motivations related to knowledge, such as the scope for a division of labour and the role of complementarity in research teams, and the narrowing of specialisation which enhances the potentials of complementarity (Winkler et al., 2015, 119); the value of diverse perspectives and diverse data collection opportunities; desires to disseminate the work broadly; the scope for division of labour within a team; the benefits of bottom-up sharing of resources, and the combined capacity to obtain funding, for example in Europe; individuals' desires for scientific status and career benefits through association with others (the preferential attachment thesis); the desire to help others, including the contribution of established scientists to younger colleagues and to capacity building in emerging systems; and also professional friendships, the psychic benefits of shared missions, interests and lives within the common professional field. There is also the deep desire to lead a breakthrough, to create something special, to hear the applause, to leave an imperishable mark. To go with glory. It seems that the joy of being first in science can scarcely be underestimated.

***Preferential attachment.*** Scholarly grounds are not the only ones in play. Collaboration is also about position and status. The narrative of preferential attachment assumes that scientists seek collaboration with other scientists in order to augment their individual reputations and career opportunities. Status is about positional hierarchy. Positions at the top are scarce but there is more room in the middle. Status in science has a referred, positive-sum aspect which allows additional prestige to be generated and transferred between people. Katz and Ronda-Pupo (2019) observe preferential attachment in science as a dynamic of 'cumulative advantage' in which 'success-breeds-success' (1047), see also Adams, 2013). The narrative of preferential attachment is so pervasive in scientometrics that it is sometimes a synonym for networked collaboration itself (e.g. Jeong et al. 2003).

Wagner and Leydesdorff (2005) emphasise the self-organising character of attachment: 'the selection of a partner and the location of the research rest on choices made by the researchers themselves rather than emerging through national or institutional incentives or constraints'. It develops through the interactions between agents (1610). They propose that co-authorship is driven by 'the self-interest of researchers to link together in search of rewards, reputation, and resources offered by a collaborative network' (1611). The empirical study focuses focus on data from Web of Science for collaborations in six disciplines in the year 2000. Networks exhibit high concentrations around leading researchers, 'highly connected nodes', that 'increase their connectivity faster than their less connected peers'. That is, 'popularity is attractive' (1611). In each field there is a large number of scientists with few international collaborators, or none, and a small number of scientists with many, whose collaborations expand at a reducing rate. The authors ascribe these deviations to novice authors clustered at modest levels of international activity, less engaged beyond the local field and less likely to attract offshore partners; and highly productive authors who reach a limit in their expansion of international links because towards the end of their careers the motivations governing successful scientists change (1613-1615). The power law operates consistently only in the long middle of the distribution (1614), where scientists 'are competing for reputation and reward in terms of international co-authorship relations using the mechanism of preferential attachment' (1615). A later study focused on six academic disciplines (Wagner at al. 2017) recognises the same power-law. Wagner and colleagues suggest preferential attachment is universal. This partly contrasts with findings by Cabanac et al. (2015) who analyse the publication records of 3,860 researchers in computer science over a thirty-year period to 2012. The study finds that early in their careers scientists network upward, consistent not only with investment in preferential attachment but with professional mentoring. Later scientists 'increasingly' work 'with confirmed researchers with whom they already collaborated', and enrol beginning researchers, those who have not previously published, as partners (135). Long-term partnerships are supported by social factors like 'homophily and acquaintanceship' and may be influenced by the subject matter of the research, institutional proximity and friendship (146).

If it is accepted that preferential attachment is at work, it nevertheless is subject to differing interpretations. Katz and Ronda-Pupo (2019) warn that: ‘It is important to note that preferential attachment found in data sets does not imply that preferential attachment is the active mechanism’ (1047). Preferential attachment is a description but not necessarily an explanation; and there are other possible explanations for the growth of networked science. The narrative of cognitive accumulation often fits the same evidence. As Kato and Ando (2017) suggest, intrinsic motivations grounded in the activity itself, and extrinsic motivations activated by rewards outside the activity, are not always in conflict, or wholly distinct (674). It can be argued that first, the practices of cognitive accumulation, and preferential attachment, provide conditions for each other; and second, that over a career the emphases placed on them, and the balance between them, tends to vary. Regardless of the operations of self-interest in networking, status in science rests on cognitive accumulation within processes of knowledge formation that are both individual and collective (Melin, 2000). Without knowledge formation there is no scientific status. At the same time, career building activity that brings people together can spark creativity. Preferential attachment derives its benefits from the extrinsic ‘economy of reputation’ (Birnholtz, 2002, 2227) yet is also rooted in self-actualisation and the desire for self-satisfaction. Preferential attachment can be seen as consistent with Ryan’s (2014) finding about the central importance of ‘internal self-concept motivation’ in science, which touches on the satisfactions of creation, of making things, and also senses of self-worth and personal achievement. Status is fluid, if not as fluid (or agent free) as knowledge. It is both socially valuable, lifting the individual within the society, and valuable to the individual *qua* individual. Cognitive accumulation also carries multiple satisfactions and meanings.

***Combining the two motivations.*** The narrative of preferential attachment is most intuitively plausible in relation to networking up, from junior scientists to senior and well published scientists with status. Does it also apply to horizontal relations between peers? As noted, the literature suggests an association between high performers and international collaboration, though causality is elusive. Adams (2013) argues that ‘excellence seeks excellence’ (559). With the reduced costs of global linking, science is increasingly ‘driven by international collaboration between elite groups' (557). Leaders in topic areas work with each other because this enables intellectual gains, and because this enables them to position themselves in optimal fashion within scientific competition. The topic leaders are disproportionately located in leading universities (Kwiek, 2018, 416) whose personnel network with parallel persons in other elite universities (Kwiek, 2010, 2 and 4). However, other scientists, with lesser publication lists and reputations, also want to work with the leaders. For Kwiek (2018) high achieving scientists are most likely to evidence intrinsic motivations, including internationalisation for cognitive reasons. Those less known as excellent might focus mostly on positioning. This suggests plural motives on a spectrum, from knowledge building to networking upwards driven by preferential attachment. Nevertheless, here again both kinds of motive may be in play simultaneously.

In dominant universities resources, intellectual synergies, intellectual excellence and social excellence, articulated by institutional hierarchies, seem to compound and reinforce each other. In this landscape the distribution of cognitive capability is not *identical* to the distribution of status or resources, but the correspondences are significant; more so because when cognitive capability is located at Harvard or Oxford it seems to gain weight. In these universities the idea of preferential attachment is consistent with both the Anglo-American hegemony which calibrates status, and the widely shared assumption that societies are inherently competitive and driven by economic or social self-interest. Nevertheless, these conjunctions are interpreted somewhat differently within the literature. King (2011) argues that preferential attachment is associated with enclosure not openness and a science system in which network power is uneven and concentrated (360). In contrast Wagner and colleagues emphasise the openness of the global system. Their vision of global science is close to imaginings of the perfect economic market. The onesideness of both formulations is problematic. In the real world attachments are both horizontal and vertical and the pervasive networked structures are both open and closed. Yet the widespread embrace of preferential attachment as a general theory is striking, and says something about the deep-seated understanding of human nature that pervades much of social science. It is ironic that in explanations which start with the need to understand the fact of cooperative knowledge formation, which constitutes shared goods ultimately outside individual control, the vision is dragged back to the familiar individualist terrain of fear, greed and glory, the Hobbesian natural order, conjured up by the chaos and misery of the English civil war, that still pervades Western culture. There is more to science than this.

In a 2004 survey of US scientists in universities and government laboratories (n= 381), combined also with semi-structured interviews with 94 researchers, Birnholz (2007) inquires directly into motivations. There was no apparent relationship between perceptions of competition in science and propensities to collaborate: that is, heightened competition neither enhanced not diminished collaboration. This undermines narratives of preferential attachment as 'caused' by competition for status, in the manner that competition in an economic market drives relations of exchange. According to Birnholz (2007), scientists resolved the antinomies of cooperation and competition through selective trust within the larger network. Being first to a discovery was a source of personal status, but researchers trusted their colleagues. At the same time, some researchers ran solitary projects alongside their joint projects because independent work could be especially effective in signalling success and status in science (2232). Birnholz (2007) also found that there was a strong positive relationship between perceived resource concentration and the propensity to collaborate; and a clear positive relationship between agreement on what constituted 'quality research' and the propensity to collaborate (2233-2234). Resources are not a sufficient explanation for collaboration and creativity in science, but they are necessary.

The interactions between extrinsic and intrinsic factors, the complexity and variety of motives for collaboration and the changeability across the course of a career all point to the unwisdom of universal theorisations of scientists' behaviours. In collaboration many factors interact. 'Their relative importance depends on the level of aggregation analysed' (Barrios et al. 2019, 633): nation, institution or discipline. Tijssen and colleagues comment that:

> Collaboration patterns and trends emerge from a highly complex adaptive system with millions of largely unseen interactions and transactions, large uncertainties about when and how people work together, significant effects of chance meetings (serendipity) and major influences of external factors such as funding mechanisms, managerial decisions or policy interventions. Numerous interconnected determinants are at play of which only a few major structural factors can be modelled at the macro-level of national research systems: Geographical borders and language, fields of science, research capacity and human resources, stage of economic development, international orientation and the existence of major research-performing universities, government laboratories or R&D-intensive companies (Tijssen et al., 2012, 2).

Preferential attachment is more plausible in modelling the motives of junior scientists than in explaining why leading scientists work with junior fellows and scientists from emerging countries with lesser formal accomplishment. The combined arrangement makes more sense if juniors also contribute to cognitive accumulation and the reproduction of professional science, and are not solely motivated by positional benefits. It seems plausible to assume that cognitive accumulation and preferential attachment are joined in most careers, though not constantly, or in the same way in every case. Shared values, collective commitments, cognitive content and positional self-interest are all in play. There is also a limit to the extent to which scientometric analyses of bibliometric data can illuminate the mixed motivations for scientific collaboration in all circumstances. As stated by Larregue et al. (2020) more nuanced techniques, closer to scientific work itself, are needed.

***Status in the global scale.*** It is plausible to argue that scientific collaboration combines motives for cognitive accumulation with the desire for status via preferential attachment. Knowledge is a common and collective global good with individual moments, while status is an individual good resting on a hierarchy within social relations. However, the relation between the two is not a constant, across the life cycle or in differing scales. Wagner et al. (2019) explain patterns of novelty in knowledge as the obverse of status flows: the first is facilitated by local proximity, while the second is optimised in the global scale. Bibliometric data do not allow cognitive accumulation to be readily distinguished from preferential attachment. Citations can signify both kinds of value: hierarchical recognition and cognitive debt. If so, why is there a change in the dynamics of cooperation and recognition when moving between scales? Why is it easier to build new status by working at the global level, even for junior researchers, than in national and local domains? Why is academic status scarcer, more zero-sum, more jealously guarded, in local and national science?

A possible explanation goes like this. In the global science system not only does networking change in character, being little articulated by nation-states, so does the status economy. The structural constraints imposed by national politics have gone. As a vacuum opens up in the politics of science, knowledge flows freely in the gaps between national systems and the potential for status production is also enhanced. The global strategic space is intrinsically more open and positive sum. The potential for growth in the status economy moves lock-step with the free expansion of the networks. More so than national networks and much more so than local ones, global networks fall short of saturation. The expansion of global networks is an expansion of the sum of available social positions and opportunities to secure advantage by networking within the growing field. Though there is competition and hierarchy in global science, scarcity is diminished. Global positionality in science is an 'empire without end', to use Virgil's 19 BCE phrase for Rome under Augustus.[1] In that regard it is not very different to knowledge because its expansion is sustained by the same network logic. At the same time, it tends towards the universal in another way. Peer review-based global science provides a single calibration of worth, a more credible standard than are the local hierarchies subject to politicking and seniority, or solely national accolades.

The fecund expansion of globally networked status rests on the fecund expansion of local/global knowledge, while the growth of knowledge is partly driven by the lure of

[1] '… young Romulus will take the leadership, build walls of Mars, and call by his own name his people Romans. For these I set no limits, world or time, But make a gift of empire without end' – Virgil, *Aeneid*, I.278–279.

status. It is noticeable that the national scale plays a modest role: policy and funding are largely outside the inner exchange between knowledge and status that has helped to power the growth of the global system. The nation has little direct role in status building in science. Indeed, expansion in the role of global status diminishes the potency of status at the national scale. The partly open positional structure of global science helps to explain the virulence of its expansionary dynamic and the seamless ease of the conjunction between strategies of knowledge building and those of preferential attachment. Nevertheless, there is an ongoing struggle between those in science who would correlate a hierarchy of knowledge value to the stratification of universities, fields and countries (the old Anglo-American empire); and proponents of a more open approach to positional and cognitive value in a global republic of knowledge, with freer scope for new science powers and heterogeneous thoughts.

In more localised strategies of preferential attachment, where cognitive proximity maximises the potential for in-field co-authorship and citation, there is less scope for the creation of new status within science. Yet 'adjacent partners' offer not just the potential for deeper and more original insights but reduced uncertainty (Hennemann et al., 2012, 224), and may invoke national or institutional solidarity. The counter argument is that competition in zero-sum local and national settings can inhibit status sharing (Wuesterman et al., 2019, p. 8). If the scientist confers status also on local colleagues, he/she may be little better off in net terms. Status shared with international colleagues has no such strategic defect. The respective weights attributed to local solidarity and competition are likely to vary according to national system norms and expectations of institutional loyalty, but where local competition is more potent than local solidarity this might further drive global association in science. Scientists need collaborators just like everyone else. But the rewards of global activity are also brought back. Preferential attachment is created internationally, in a positive sum exchange of status between partners. Yet the value of that status is largely (though not solely) realised at home where most career rewards are allocated. Scientists secure global status that is intrinsically satisfying *and* propels them up local hierarchies. ~In the absence of global cognitive accumulation it would not happen. It is possible to imagine cognitive accumulation without behaviours designed to secure preferential attachment, but hard to imagine preferential attachment without any cognitive accumulation taking place.

**Locality, distance and creativity**

As discussed, Tijssen et al. (2012) and Waltman et al. (2011) identify a continuous expansion in average geographical distance per collaboration. More significant is the difference between global and national/local spatiality in science that various studies suggest. National, and especially local, relations are partly conducted in real places in face-to-face interactions. They are partly geography-bound. Global relations are mostly virtual and given the low unit costs of linkages are conducted with anywhere and freely expand outwards. Nevertheless, occasional face to face meetings underpin stronger virtual collaborations:

> … although the great advancements of telecommunication technology have created new possibilities for countries located far away to form collaborative linkages with one another … geographical proximity still has a significant influence on international research collaboration, because the face-to-face contacts enable more complex and intense forms of interactions in which not only language is involved but also the entire behavioural complex (such as subtle communication, informal interaction), which cannot easily be achieved with the assistance of modern communication media (Chen et al., 2019, 160).

Because local/national and global collaborations have partly differing drivers, both can increase at the same time. Analysing scientific collaboration in six different disciplinary fields, which display similar patterns, Hennemann et al. (2012) find that there is 'no sign' that 'frontier science … is a highly internationalised activity'; and the probability of national collaboration is 'much higher' than is the case with international collaboration, though international collaboration may be concentrated in high impact areas. Their study also finds that the factor of distance itself plays out differently between on one hand the global system, on the other hand national and local science. They find that 'strong dependencies exist between collaborative activity (measured in co-authorships) and spatial distance when confined to national borders' (217). 'Much human interaction is involved in scientific knowledge creation

…. Spatial proximity is a large driver in this process' (224). Locality wins. The rate of collaboration is inversely proportional to distance, at least where the geographical gap is modest. However, 'distance becomes irrelevant once collaboration is taken to the international scale' (217). In the global system, communications technologies enable 'cognitive proximity' (218). In other words, at the longer distances where the normal contact is virtual, geography ceases to determining. This 'saves the idea of the globalized science system … science is indeed global once it has left the strong influence of the national sphere and the gravitational pull of local science clusters' (224).

This suggests that there are two kinds of relation between spatiality and networked scientific activity. One relation is global and distance-neutral. The other relation is national but primarily local, and place-based. Tijssen et al. (2012) reach a similar conclusion. They state that proximity is 'a major determining factor' in relation to local or national collaboration, but not in relation to global collaboration, where the expansion of the network increasing the average distance, is accompanied by growth of papers (2). Hennemann et al. (2012) conclude that given that intra-country collaborations are more likely to occur than global collaborations, this suggests a combination of strong place-bound national systems coupled to a place-open global system: 'a globalised science system that is strongly affected by the gravity of local science structures' (217). At the same time, while publication data as such do not reveal the degree of intensity of collaboration (Graf and Kalthaus, 2018, 13), national-local ties may be more deeply felt than the loose ties typical of global relations that are mediated by technology and non-mandatory recognition.

Wagner et al. (2019) compare internationally co-authored papers with other papers in terms of intellectual novelty. They assume that in significant innovations, existing literature is combined with literature that is novel to the topic, and test papers with this combination of characteristics for citation outcomes. Novel contributions entail risks, especially if they combine different disciplines or otherwise break with established patterns, and also entail lag time before the new idea is accepted.
The authors find that on the whole, international collaboration is less intellectually adventurous. It appears to produce 'less novel and more conventional knowledge

combinations’ (1). The data for all fields show a negative correlation between number of countries of authorship and novelty, and a positive correlation between number of countries of authorship and conventionality. The researchers find that in six disciplinary fields, ‘international collaboration was either positively associated with conventionality or negatively associated with novelty or non-significant’ (5). At the same time, they find a positive association between number of authors and novelty. Hence not number of authors but country spread inhibits novelty.

The researchers advance a number of possible explanations. One is the ‘transaction costs’ of collaboration which can reduce cognitive accumulation. Wagner et al. (2019) state that ‘international collaboration may lean towards more hierarchical governance centralized around single or fewer leaders. Differing worldviews, nomenclatures, languages, and expectations can have the effect of slowing the integration of ideas, and may encumber the quality and validity of the results’ (6). Language differences within collaborative teams may ‘reduce opportunities for highly creative discussion that would lead to novel work among collaborators’ (7). Further, the need to rely on information and communications technologies ‘limits the ability to share tacit or implicit knowledge … ICTs favor the transmission of knowledge that can be codified and reduced to data’ (7).

> ICTs do not facilitate the exchange of tacit knowledge, defined as the tradition, inherited practices, implied values, and prejudgments held by people involved in a communications process … These processes occur at an interpersonal level and are much richer in person than through a written medium. It may be that ICTs cannot substitute for the exchange of tacit knowledge as a critical component of innovation that take place face-to-face. The process of drawing conclusions and making observations will likely occur in a linear fashion, whereas theory suggests that innovation is an iterative process of divergence and convergence in concentric circles (Wagner et al., 2019, 7-8).

The point about tacit knowledge and creativity is made elsewhere in the literature. Katz and Martin (1997) cite earlier studies showing that ‘spatial proximity seems to encourage collaboration since it tends to generate more informal communication’ (5).

However, while such factors explain why there is more innovation in local collaborations, they do not explain why international work is more highly cited. Wagner et al. (2019) explain this by arguing that ‘the findings are consistent with explanations of growth in international collaboration that posit a social dynamic of preferential attachment based on reputation’ (1). The ‘citation strength of international work reflects network strength as much or more than quality and novelty’ (9), that is, cognitive accumulation based on originality of thought. International collaboration is a ‘force multiplier’ for growing readership and citation (8) and elite scholars generate referred status among both collaborators and citers. ‘Within networks, reputation is a core driver of cohesion’ (9). International work is more highly cited because it carries greater status, in a circular process of reaffirmation. Bhattacharya and Packalen (2020) likewise identify a divergence between international citations and path-breaking novelty. For them, the quest for citation recognition fosters ‘incremental science’. Path-breaking science based on local collaboration is slower to be accepted and taken up and has a narrower reach. For both reasons it has a lesser potential to achieve recognition.

A limitation of the Wagner et al. (2019) study is that all single country papers are classified in common: the researchers do not distinguish between local-level and national-level collaborations. As noted, Wuesterman et al. (2019) work with national, sub-national regional and local scales. They focus on citation patterns in life sciences and medicine, investigating the probability that articles published in 2014 cited articles published in 2012. Previous studies indicate a geographical bias in citation: citations occur more frequently within countries than between countries, and further concentrate within organisations. The researchers suggest this can be explained by both familiarity - scientists are more likely to give recognition to work or institutions that they know, especially if they share an identity or tacit knowledge with the authors, and this factor is liable to geographic bias – and also knowledge-relatedness. Common intellectual conversations are geographically patterned. Wuesterman et al. (2019) measure knowledge-relatedness by computing the number of references shared between the citing article and the cited article. They find that the effect of geographical co-location is much greater at the organisational level (shared institution), than at the sub-national regional level, and weaker at the national level. When the effect of co-location is accounted for, the geographical bias in citation largely disappears (2). ‘The largest part of the geographic bias in scientific citations is explained by the geographical concentration of related knowledge’ (8). Again, locality wins. The main difference is not between the national and global scales, but between the local scale and all others.

However, in the case of articles highly related in terms of knowledge, geographical effects disappear. Distance is no longer a barrier. Frenken et al. (2009) make a similar point about co-authorship: ‘physical proximity is helpful in many forms of scientific interaction, but it is expected to be less important if two researchers are proximate in, say, the cognitive dimension. In the latter case, interaction through the Internet is expected to be very effective’ (230). Strikingly, and like Wagner at al. (2019), Wuesterman et al. (2019) also find that proximity is a potent factor in the originality of science. The global system is more limited in terms of novelty and intellectual risk taking. In the case of articles where knowledge-relatedness is *low*, for example contrasting disciplinary literatures, co-location ‘particularly increases the likelihood of citation’ (2), especially co-location at the organisational level (8). Where there is no bibliographic coupling at all between the first paper and the paper in which it is used, citation is 14.8 times more likely at organisational level, 4.2 times more likely at regional level and just 2.3 times more likely at national level (7). This suggests that ‘the institutionalization of science in localized campuses may be especially beneficial’ for inter-disciplinary innovations (2). As well as being more likely to meet persons from outside their immediate field at the local level, scientists are less likely to be in direct competition with them (8). The researchers also find that ‘cognitively-related knowledge may be geographically concentrated as well’ (1); and anyway, when knowledge-relatedness is high, scale has no effect on the potential for citation. Hence local proximity both maximises knowledge-relatedness and maximises the potential payoffs from *non* knowledge-relatedness. Given the growth of collaboration in science, these findings infer that first, the expansion of networked global and national science represents an expansion of common conversations in zones of shared knowledge where locality is unimportant to the structure of communications (though it may influence content); second, there is little national-level filtering of citation recognition, third, the potential for epistemological breaks is facilitated by proximate non-cognitive association. The local scale maximises both the likelihood of knowledge commonality and fruitful interaction between fields. All else equal it has a larger creative potential than does cross-border interaction mediated by the Internet.

The findings of Wuesterman et al. (2019) are consistent with the global/local vision of Wagner et al. (2015) rather than with studies emphasising the national system domain. They draw attention to the limitations of research that defines local effects as inherently 'national', pointing to the need to break open the black box of national systems and work with the different scales within it. Their study does not obviate the role of cross-country teams in innovation but suggests that overall, this role is maximised within established fields of knowledge and lines of inquiry rather than in risk taking off-the-wall initiatives. At the same time, there are always exceptions to such generalisations – examples of world-spanning work in which strong people in a field interact to produce major innovations.

The overall picture is that of a global/local division of labour in which cutting-edge innovations are disproportionately sourced on the basis of local collaboration before being circulated and generalised in the global system; while again, the global system is an especially potent source of status, and status bulks larger vis a vis discovery in the global scale. Global status has a positive sum dynamic, overshadowing national and local sources of esteem, until it translates back into the tighter national-local positional structures.

**Agency of emerging national systems**

In a succession of investigations Chinchilla-Rodriguez and colleagues attempt to isolate the potentials for national agency within world science, focusing on autonomy in emerging country systems. They question they ask is, what is the scope for subaltern national science systems to improve comparative performance and global position, with or without the device of cross-border collaboration? Chinchilla-Rodriguez and colleagues understand science worldwide not as a combination of autonomous global system and heterogeneous national systems, which is the conception used in the present paper, but in terms of world-systems theory with its division of labour between a Euro-American centric centre/core and dependant countries on the periphery, with national systems that are located in the intermediate semi-periphery lying in between (Wallerstein, 1974; Olechnika et all. 2019). World systems theory can be criticised for its inability to conceive a global domain separate from the mosaic of nations, and the fixed character of its category distinctions between nations, the assumption that all non-centre nations are caught in a dependency trap (Smith, 1979; Marginson and Xu, 2021), but has the virtue of focusing directly on relations of power. Chinchilla-Rodriguez and colleagues have a more open conception of world-systems than in the classical expression of world-systems theory by Wallerstein (1974), though they run up against the limitations of scientometric assumptions and methods.

Chinchilla-Rodriguez et al. (2019) argue that national agency in science is established by economic capacity, national policy and priorities, and 'institutional settings and cultures' (1). 'Scientific relations are highly resource-dependent' and this plays directly into global inequalities (Chinchilla-Rodriguez et al. 2018b, 588). Countries with higher investment in R&D are 'more scientifically independent' (Chinchilla-Rodriguez et al. 2019, 1 and 6). National capacity in science is understood in terms of resources and international collaboration but both carry dangers for autonomy, which is constrained by the need to obtain funding and the agendas of those who provide it (Chinchilla-Rodriguez et al., 2018a, 1486). Funding must enter any understanding of national science. However, the researchers find that international collaboration is ambiguous, and national systemic autonomy is difficult to pin down with the methods they use to measure it.

The researchers rightly note that autonomy is both resource-based and a matter of cultural power. For them the keys to national self-determination are resistance to 'foreign knowledge', the fostering of local concepts and methods (Chinchilla-Rodriguez et al., 2018a, 1486), and endogenous capacity:

> Simply put, the greater the scientific capacity of a country, the more internalised the production … the more a country invests in R&D, the greater its capacity for creating infrastructure, training skilled researchers, attracting talent and creating cohesion among domestic institutions' (Chinchilla-Rodriguez et al. 2019, 6).

However, their proxy measures of autonomy are not sufficient to achieve a clear profile of self-determination sufficient to ground the kind of universal conclusions required by the methodology of scientometrics. It is doubtful if any measures could serve: dualistic black/white indicators and universal patterns conflict with the need to contextualise issues of power and strategy for each national case, as they themselves show, and the ambiguity of the indicator data in the real world. Chinchilla-Rodriguez et al. (2018a) define the autonomy of emerging countries in terms of whether there is a low rate of international collaboration, which means greater autonomy, and whether authors are first named or corresponding author, again said to indicate autonomy. They are right to argue – against most wisdom of the field – that follower co-authorship can indicate a dependence that retards national capacity rather than building it. However, it is simplistic to render all collaboration as negative autonomy; and when they investigate the relations between autonomy/dependence as they define it, and the output and citation rate of papers (1488), they find that autonomy does not necessarily equate to higher research performance in orthodox terms. Research performance is measured by paper output and high citations. While the follower co-authorship as seen as always negative, indicating low autonomy, citation of national work is seen as an always positive sign of performance (Chinchilla-Rodriguez et al., 2018a, 1501); so that their two different measures of global connectedness are pitched against each other; and as they themselves note; while international collaboration increases citation impact, 'there are different underlying reasons', and there is variation on a country by country basis and on the basis of the partners (1498).

None of the universal assumptions hold. Not all second co-authorship is a sign of weakness; not all citation signifies positive performance; and like co-authorship (or any publication in global journals), citation may indicate conformity with dominant agendas. Empirically the citation performance of papers based on solely national papers collaboration, or lead authorship, varies by country. China and India both gain little in global citations from collaboration, indicating high autonomy, but global citation rates for nationally led and nationally authored papers are higher in China than India (Chinchilla-Rodriguez et al., 2018a, 1493). Chile and Cuba both have high 'technological impact' but whereas Chile achieves this impact in nanotechnology through international co-authorship, Cuban authors practice 'nearly total autonomy' (1493) and are more productive in lead position (1496). High collaboration plus a high incidence of leadership on collaborative papers can be 'an indicator of either research isolation (for small and developing countries) or of consolidated scientific systems (for well-resourced countries)' (Chinchilla-Rodriguez et al. 2019, 12). More fundamentally, autonomy as cultural power could be expressed outside the orthodox indicators – for example more published papers in languages other than English – but when all indicators of performance are derived from the global system this cannot register, so the autonomy is invisible.

Consistent with the logic of the centre-periphery theory cited by Chinchilla-Rodriguez and colleagues, these studies suggest a trade-off between on one hand high autonomy and low performance; on the other hand, low autonomy but high performance, so that autonomous development is always constrained by global power (see also Olechnicka et al. 2019). Yet the data indicate the potential for high autonomy and high performance in emerging systems outside the Euro-American centres, for example systems like China that work partly inside and partly outside the dominant framework in global science. Further, in the indicators used by Chinchilla-Rodriguez and colleagues, one proxy for capacity, which is international collaboration, is pitched directly against autonomous agency; while the other proxy for capacity, finance, is treated as congruent to autonomous agency. The notion of national capacity is split, suggesting that in emerging systems strong and autonomous capacity can be built only in a parallel universe outside the centre-periphery world-system.

Despite these problems, the product of normative and universal framing designed to establish statistical relations, the studies by Chinchilla-Rodriguez and colleagues enable insight into two distinct pathways in emerging country systems, as was suggested also in Table 2 and Figure 2. One pathway emphasises national infrastructure and capacity building, and nationally based networks, with relatively high growth in national co-authorships, for example India, China and South Korea. On the other pathway nations use international collaboration as the main means of extending national capacity. Smaller countries like Azerbaijan, Peru and Panama 'depend almost exclusively on international collaboration for their output, with low degrees of domestic collaboration and sole authorship' (Chinchilla-Rodriguez et al. 2019, 5). Jang and Ko likewise find that the 13 'late comer' countries in their study, characterised by an 'exponential rise' in publications and citations (447), divided into 'a group that maintained an "independent" research climate with emphasis on the national system (China and Iran), and a "cooperative" group that emphasizes international collaboration (e.g., Colombia and Armenia)' (475). As noted above, China has moved in both ways at the same time, building national networks while pursuing a high volume of international collaborations, especially in the US. The two pathways again confirm that indicators like rates of international or national collaboration, or lead authorship, have multiple meanings. For example, in many nations, nation-only papers are less cited globally, but not in all. in their study of BRICS and Latin American countries in nanoscience, Chinchilla-Rodriguez et al. (2018b) find that Brazil performs better in the global citation of its nation-only papers than its internationally co-authored papers (1493). Adams (2013) finds that in China, the top 10 per cent of nation-only papers had citation rates double the world average (558).

Chinchilla-Rodriguez et al. (2018b) progress in defining national science systems though they are constrained by the combination of methodological globalism and methodological nationalism which typifies most of scientometrics. They hold global citation (though not collaboration) as a universal sign of performance. They separate out part of the global network, while using global bibliometric data to define the element so separated, then brand this as a potentially autonomous nation. But standardised global indicators, that calibrate national science in an incomplete fashion relative to other countries without contextualising it, cannot adequately define national science, or ground autonomy, without a full picture of national science, or an understanding of the overlap between national science and global science. National autonomy is defined in the global/national relation. It is impossible to explain where the national system overlaps with the global system without admitting that the same object can have two meanings, which might be synergistic or in tension, and that the resolution is contextualised - and it is impossible to investigate multiple identity and context without moving beyond the analysis of bibliometric data.

## Conclusion: Relations between global and national science

Science is a constellation of four interdependent elements. First, there is knowledge, which is both individual and collective in genesis but primarily collective, additive and positive sum. Knowledge is not subject to the logic of scarcity. It can grow much faster than financial investment but needs a baseline level of resources and a communication system in which to be produced, exchanged and disseminated. While the value of knowledge is not determined by scarcity or market forces it is calibrated by institutional, disciplinary and professional hierarchies and subject to cultural biases and exclusions. Second, there are scientists themselves, the people who produce and publish knowledge and collaborate locally, nationally and globally in doing so. Third, there is the networked communication system which sustains collaborative relations and facilitates cognitive accumulation in the form of data sharing, joint analysis and summative texts. All else being equal communicative technologies tend to quicken scientific work as instantaneous messaging and visibility are themselves stimulating motivators, calling up additional output through reciprocal flows. Fourth, there are resources for science, which are primarily national and institutional in origin, and the institutional and regulatory frameworks in which science happens. National and institutional rules and resourcing can either speed or retard networked association and knowledge production. Governments and universities can enhance or retard autonomous output and they can also advance or retard heteronomous output. Science is essentially about relations between these elements – knowledge, people, networked communications and the national/institutional setting – but the content of each can vary. People are the constant in science, but there are two-way and three-way interdependencies between resources, knowledge and the networks that sustain the far-reaching sociability of scientists and their institutions. These interdependencies are one pathway for further inquiry.

This conclusion summarises the paper's discussion of scale, and science in the global scale, and expands on the relations between global science and the national science systems. The final section draws out some of the implications for social theory, arguing for an ontology which frees up the explanatory power of heterogeneity and multiplicity.

**Scale in the study of science**

The primary conceptual instrument of this paper is geo-spatial *scale*. Whether it is directly acknowledged or not, scale plays a central role in many studies of science, a role that is increasing because of the growth of global science and the globally inclusive data set used in bibliometric studies. Whenever the global data are translated into national sets or comparisons, or interrogated using institutional signifiers, assumptions about scale and the relations between scales are entailed. The paper has made explicit the dimension of scale, highlighted the heterogeneity of scales – global and national science are qualitatively different in important ways – and has focused on relations between the scales.

Scale incorporates both materiality and interpretation/perception (Herod, 2008). A key weakness of many studies of globalisation, and of nations in the global setting, is that interpretation often overwhelms materiality. There is a disjunction between the normative and empirical frames, in which the living reality is normatively subsumed by what the observer wants to see or expects to see. There are two variations of this error. On one hand, a minority of analyses imagine that the nation-state is becoming weaker or is dissolving amid the processes of global integration and convergence. These 'globalist' studies neglect the continuing material potency of the nation-state, for example in science where government remains the most important single agent in the financing and regulation of universities and basic scientific research. On the other hand, a much larger group of studies impose a wholly national framework on the analysis of science and relations in science, treating relational cross-border dynamics, such as networks and collaboration, as a function of national activity alone, and arbitrarily splitting global data sets into zero-sum national categories – despite warnings within the same literature that this might be problematic, beginning with May (1997). Methodological nationalism is an act of power that sustain the ‘imagined community’ (Anderson, 2006) of the nation. The cost, however, is explanation: it negates any possibility of seeing or understanding global science as a system. In turn this means relations between national and global science remain a black box. Yet national science does not emerge in full either, as global bibliometric data include only global papers. Such studies reveal more about perceptions of science than about science itself.

As discussed, scientometrics includes interesting studies which use multiple scales, but there is little theorisation of scale as such, and the most common approach to multiple scale is to read scales in terms of different levels of aggregation within a single data set – as if scale is patterned by scale invariance. The possibility that scales are heterogenous, with differing forms, implications for agency and relational dynamics, is little considered; though some studies by Leydesdorff, Wagner and colleagues point in this direction.

In research on science systems, normative globalism and nationalism are each associated with problematic assumptions. Standard analyses imagine that cross-border collaborations as driven by the strategies, capabilities or resources of nations or ‘their’ institutions (methodological nationalism); and the level of such global relations is positively correlated to ‘quality’ or ‘performance’ (methodological globalism). Neither of these assumptions is necessarily true. Collaboration is at least partly driven by global communities and local action, at some distance from national agency. The comparative data suggest that relatively high levels and low levels of collaboration are each associated with high and low capacity national science. Nor do citations signify unambiguous quality or a constant standard of value. Collaboration and citation data each signify connections, but are both highly multiple in character. No single narrative applies. Each are nested in different narratives; though it must be said that in collaboration and citation, cognitive accumulation is never completely absent. Collective knowledge is an irreducible component of science.

All of this suggests that the burgeoning 'science of science policy' (Cimini et al.; 2016), which attempts to establish linear cause-effect relations between science and the economy, to measure efficiency in these relations, and thereby enhance the performance of national science, is inherently problematic. The 'science of science policy' uses bibliometric data to establish decontextualised national comparisons, sees rates of international collaboration and citation as positive indicators of performance, and attempts to link these apparently uniform measures on one hand to financial inputs and on the other to economic innovation and GDP accumulation. At best this runs the risk of over-simplification. At worst it gravely reifies actual scientific and economic practices. When comparative data are left to stand on their own, for example without contextual information, this invites unsecured explanations; but there is also the more fundamental problem of scale. In reality science routinely spills out across borders. Capital accumulation also operates freely across borders. In any case the circuits of knowledge and the circuits of capital are separate and heterogeneous. Science is at least partly autonomous from both states and economies. To suggest otherwise, and through narrative, theory or method to attempt to persuade others to do the same, is to be complicit in violating that autonomy, which is never completely secure. Better to explore national science systems on the basis of closely contextualised studies that take in the full range of national activity, whether or not it is included in Web of Science and Scopus. This is especially necessary in relation to countries where the first language of use is not English.

**Global science**

In the era of communicative globalisation all information-based social systems have undergone a similar process of accelerated and comprehensive development in which the global scale has become much more developed. Here science might be distinctive. Though universities and higher education are more globalised than are most social sectors, it can be argued that their centre of gravity remains the national system, even in the elite research universities that are strongly implicated in global comparisons and connections. This is attested empirically by interviews by Friedman (2018) with the leaders of front-rank Anglo-American universities. He finds that in the end, 'everyday nationalism' predominates. Though the matter is difficult to pin down, it may be different in science. Powerful scientific knowledge, the ideas, are powerful across the whole domain of modernity. The universality of scientific languages and content carries much with it. Global science networks would not exist without national funding. Yet those same global networks may lead in cognitive accumulation, at least in many disciplines, and be more potent than national networks in the production and allocation of status in science. States have little direct role in generating scientific content and though global status must be realised at home to carry weight, in most countries national scientific status alone is less potent than global status. The main exception is the United States of America, the hegemonic country, for nations that deeply believe themselves to be the centre of the universe are always self-referenced. There is something of this hubris also in the old imperial nations, Britain and France, and Russia and Japan. Perhaps it will take root in China. But science has an irreducible meritocratic element. It is impossible to completely screen out the value of the rest of the world, even in the US.

The differences between global and national science have been primary to this paper. Global science is a self-regulating network, where the outer border (unlike the border in national systems) imposes no constraint, and in formal terms there is freedom of association within the system. As noted, global science is grounded in the cultural practices of science itself, local science (it has been especially influenced by US faculty culture) and the normal operations of relatively autonomous networks. It may seem strange to talk of autonomy in relation to countries where universities have overt political pressure from governments – not just Turkey where their personnel are suppressed, but China and Singapore where they are thoroughly embedded in the state, and now the US where they are pressured to 'voluntarily' break their cooperation with counterparts in China. It may also seem strange to talk of autonomy given that in most countries the material basis for the independent professoriate is being eroded in one respect: the role of tenured posts within academic labour is declining and there is a growing precarity affecting most early career researchers. Yet established scientists routinely achieve substantial autonomy – providing they have funding – and all scientists, junior and senior, have more scope for agency in the growing global scale than elsewhere. Here there is a counter-intuitive relation between the national resourcing of science and its partly decoupled global freedoms. An increase in national economic resources might be expected to expand the scope and intensity of national government control but often the opposite is the case. Once the funding is granted (that is the threshold moment with government influence is maximised), the extra resources can actually enhance the independent capabilities of scientists, all else being equal.

How can science as a social system be understood? Family, local community, state, market, industry, religious order or Freemason's Guild? Which analogues apply best? Modelling global science as an economy falls short of modelling its dynamics. Whatever shapes the behaviour of scientists, and there are many intrinsic and extrinsic factors, profit is not the primary force at work. Funding is a necessary condition of global science but not a sufficient explanation. Global science is not primarily driven by capitalism. Global capital moves freely between countries, as does science, but knowledge and money pass through separated circuits of exchange. It is notable that to the extent that economic imperatives affect global science, these are nation state-driven not market-driven. More remarkably given the practical links between government and scientific infrastructure, *global* science is not primarily driven by politics either. National science is politically shaped but global science is not. The nearest macro-social term that applies to global science is 'civil society'.

The point cannot be emphasised too strongly – global science is powered by a largely unregulated network dynamic in which its practitioners shape their own order. Its strengths and limitations, its collectivities, closures and biases, are their responsibility. All scientists are touched by their national and institutional settings but regardless of the political system, when they go global there is typically a high degree of freedom in relation to cognitive accumulation – at least for the fortunate agents whose work falls within the globally-defined boundaries of legitimacy. In empirical terms the growth of unregulated global science has followed the pathways theorised in Castells's (2000, 2002) explanation of global networks. Social network analysis implies a polarity between network extension and metropolitan concentrations. Castells understands networks better. He states that both tend to advance simultaneously. Global science networks build local concentrations of capacity and also vice versa. In measures of network centrality this shows as an unstable oscillation between dispersion and concentration. As is often the case, the analytical instruments are more singular and categorically zero-sum than the reality they track. Likewise, as they grow, global scientific networks are characterised by both increasing openness and increasing instances of and scope for closure. However, there is a discernible tendency to multi-polarity in the capacity of national systems. In that sense scientific output is increasingly dispersed. This in itself fosters an openness simply because more distributed network power reduces the scope for monopoly and oligopoly. The old Euro-American core is less dominant in paper numbers and citation patterns. Yet the Euro-American core remains culturally dominant, perhaps to a surprising extent. There is a lag between shifts in the political economy and shifts in hegemonic cultural power so that in the space between the two, there is a world in which Western science is becoming multi-centred. But sooner or later, political economic power tends to transfer into cultural power. Science will change, and ultimately more through the evolution of unregulated scientific cooperation than the play of competition and cooperation within the inflexible mosaic of bordered nation-states.

This paper has emphasised the heterogeneity of the scales. The factor of autonomy is one key to that heterogeneity: by definition, intrinsic factors are especially important in explaining the autonomous global system, the domain of a purer science, whereas in national science systems and administered institutional spaces, the role of extrinsic factors is obvious. This is not to say that intrinsic factors are absent in the national and local scales – cognitive accumulation and preferential attachment occur everywhere. But the scales have differing implications for negative and positive freedom, or what Sen (1985; 1992) calls control freedom and effective freedom. The national scale has resources that are essential to effective freedom in science but is also more constrained, by the normative centre of the nation-state and by the ‘little nation’ that is its form in the university. Agency freedom in science soars above all in the global scale, the scale of the limitless imagination, or so it seems. Leading scientists often break free of control over content because of the mysteries of their work. Only the limits of resources constrain them. That tethers them to the local and national settings and is the primary means whereby they can be controlled (direct interference in intellectual decisions has limits). But their global freedoms remain potent, not least because leading scientists have individual value and can move, if necessary to another set of resource configurations: global status in science translated Bourdieu-style into economic and administrative capital. Perhaps the balance between preferential attachment and cognitive accumulation changes when science moves to the global scale because of changes in the respective potencies of each. Some have suggested that the potential for cognitive innovations, especially those entailing epistemological breaks, is greater in the national than the global scale, though that is primarily because the organic local scale has the potential to foster sustained and deep interactions, across as well as within fields (e.g. Wagner, et al., 2019; Wuesterman, et al., 2019). In contrast, it seems that preferential attachment flourishes more in the global scale: global fame trumps local and even national fame, as noted (Wagner, et al., 2019). Nevertheless, the respective characters of activity and agency in each scale is a matter for further empirical test.

What can be asserted with confidence is that while cognitive accumulation and preferential attachment often combine, it is possible to have networked scientific output without preferential attachment. It is not possible to imagine preferential attachment without cognitive accumulation. Again, knowledge shows itself as foundational in this sector the key to explaining the sociability of science, and its potential for autonomous agency: knowledge is the one indispensable and most distinctive aspect the constitutes science. Those scholars of science for whom preferential attachment is more fundamental (and exciting) than cognitive accumulation have been sadly captured by the market imaginary.

The scales differ in their implications for networked expansion in science. They have different growth dynamics. This paper has also emphasised that because the national scale is contextualised – every nation-building trajectory in science is partly distinctive - the differences between national and global scales play out in varying ways from case to case.

It seems that while global growth has no evident ceiling, the expansion of nation-only networking reaches a ceiling, in its rate of growth and in some cases its absolute size, as is evident in the mature systems identified in Table 2 and Figure 2. This ceiling in nation-only networking probably derives from on one hand a limit to the resource-fed growth of national scientific capacity (constituting a limit to the positive-sum addition of national and global activity), on the other hand a limit to which scientific development can be confined to national borders when there are far more potential partners outside the country than inside it (a zero-sum relation between national and global networking kicks in). The same data, and other studies such as Olechnicka et al. (2019), show that at an earlier stage, countries are engaged in robust national system building. The emerging countries nevertheless vary notably in the balance between national network growth and global network growth. In many cases global co-authorship is growing even faster than national co-authorship. There is also a handful of countries, of which India has the largest science system, where national network growth actually outstrips global network growth. Time will tell if the national dynamics can ever be so strong that they permanently trump the dynamics of the global science system. It seems unlikely, but if it is possible it is most likely to happen in large countries such as India, China or Russia with many potential domestic partners. It is more likely to happen if geo-political tensions (for example the US-China imbroglio) trumped the global science dynamic and the global system was split or otherwise weakened.

But science is not there yet and the global dynamic appears oddly robust. The global system seems to hang in the void, like a lone galaxy slowly turning in space, but it has multiple anchors scattered between the many disciplinary communities and the many science-active nations, and this provides more security for its independence than a single central government could provide. The overall picture that emerges is that of ‘a globalised science system that is strongly affected by the gravity of local science structures’ (Hennemann, et al., 2014). Here ‘gravity’ has more than one component. First, there is the kind of measurable material weight that can be quantified; for example, the pull exerted by the metropolitan concentrations of scientific activity that are simultaneously sustained by global networking, national resources and local-institutional organisation. Here, using the tools of bibliometrics and network analysis it is possible to identify two kinds of relation between spatiality and networked systems. One relation is global in scale and distance neutral and works especially well when collaborators share strong ‘knowledge-relatedness’ (Wuesterman, et al., 2019). The other is primarily local (not national) and place based, with a negative correlation between fecundity and distance, and a greater scope for intellectual novelty. Second, there is gravity in the sense of hegemonic cultural weight, which has no intrinsic relationship to distance, and cannot be adequately measured using bibliometrics and network analysis. It requires theorisation of global relations of power (see Marginson, 2021b; Marginson and Xu, 2021). Global science might be autonomous and free for its practitioners, but this is not to say that it is inclusive and still less that it is non-hierarchical.

Science is culturally specific. Perhaps it is more like the Freemason’s Guild than the village commons. There are many exclusions and many non-practitioners in the science defined by global bibliometrics – where science is finally regulated not by scientists themselves but by two large commercial companies, though in matters of content they must take their cues from the non-profit universities and scholarly communities that are located closest to them. Elsevier and Clarivate Analytics are both locked into and also lock in the cultural control system in science. Science is ordered by Euro-American epistemology and norms of professional practice, and is dominated by the leading Anglo-American universities and their networks and journals (Marginson and Xu, 2021). Work in other languages is largely excluded from the global pool and inaccessible to most readers, even when included, because translation is undeveloped or non-existent. Endogenous constructions of science are wholly excluded. Even a domain as fecund and developed as Chinese medicine is subordinated and partly excluded by these mechanisms, while the many endogenous insights into ecological sustainability are solely localised, hidden from history, while the global science that supports the global fossil fuel industry is very globally apparent. The fact must be faced: all of those conducting scientometric analyses using bibliometric data, who take as definitive this construction of legitimate global knowledge and especially those who are untroubled by the violent exclusions (of knowledge, of persons) that are entailed, are wholly complicit in these relations of power.

Hegemony in science is exerted especially through global communications, which standardise cultural content much more readily than do organic social relations. The kind of agency that sustains resistance is mostly rooted, local, and that is both a strength and a limitation. The global tools can be used more than one way. If the push-back against global hegemony in science began to be free of the constraints of distance, if there was a distributed commonality (a unity-in-diversity) in that resistance, that would be a sign that a counter hegemony, albeit one less centralised and more inclusive, was emerging.

**The global/national intersection**

Relations between the autonomous global science system and national science systems, systems heterogeneous but overlapping and synergistic, are central to the evolution of knowledge production and the spread of knowledge. National science is a necessary condition of global science but it is not a sufficient condition. Not quite reciprocally, while global science catalyses the growth of national science, in strict terms it is neither necessary nor sufficient for national science. Yet now that global science has become so important it seems that national science cannot do without it. Novelty in science is deeply seductive, and novelty is often globally shaped, or at least not confined by national borders.

There are many points of practical intersection between the scale-based systems. As noted, the principal nodes in science are points where nation and institution meet the global network. In the zone of multiple objects, the main objects are people: scientists and university leaders adept in both realms. Modern universities are an institutional form custom-built to multiple objects. Clark Kerr's (2001) theorisation of the 'multiversity' points to its capacity for a plethora of agendas, the way it routinely sustains different lines of accountability simultaneously, and houses faculty who are both locally and institutionally nested (sometimes loosely so) while loyal to disciplinary communities. The multiple character of the US university, the institutional form now hegemonic in world higher education, has facilitated the growth of global science. It has fostered global science as part of the multiversity largely without tension with national science, at least until recently.

The dynamism might belong to networked relations and hence above all to global science, but material resources, and laws, policies and prohibitions, always matter. What are the factors that knit together this odd combination of global and national systems?

***Synergies.*** There are at least three ways the connectivity between the heterogeneous global and national science systems can be described. Each captures part of the relation.

First, as suggested, global and national science provide positive conditions for each other. International cooperation in science rests on nationally ordered infrastructures, while its fruits are seen to advance national development in science (Georghiou, 1998). These are the points most discussed in the literature. Graf and Kalthaus (2018) investigate this mutual conditionality. They compare countries' 'embeddedness in the global photovoltaics network' in 1980-2015 in relation to differing national policy factors and the structure and functionality of national science systems. 'Embeddedness', measured by network centrality, including the number of collaborating countries and the intensity of connections, means better access to knowledge, with positive effects in national innovation (1). The authors find that internally cohesive and connected science systems are well connected internationally, though less so in emerging science systems than OECD systems. National systems with scope for grassroots-initiated science and effective internal diffusion mechanisms tend to be more effective in handling external global knowledge flows. Such a virtuous national system can be fostered by policy, including public procurement, though the effects of R&D investment are ambiguous. The study suggests that all of global embeddedness, national centralisation and grass-roots freedoms can be mutually conditioning but only under specific conditions. Like most such studies it uses criteria tailored to the Euro-American bloc and tends to find that this bloc generates the best outcomes. But in any case, this kind of explanation is more about how global and national science can effectively co-exist; and about how to optimise the global effectiveness of national science. It does not explain why national and global science *need* each other, and how the *difference* (heterogeneity) between national and global systems enables each to provide something the other lacks.

Second, the global/national synergy can be understood as a division of labour. In this narrative the national and local scales foster science organically, providing it with a stable legal, institutional and financial framework and a social lattice, connecting it to applications in policy, industry and community; while the global scale motivates collaboration, distributes global status in science and structures many of the leading conversations. As noted, Wagner et al. (2019) suggest that local science often supplies the breakthrough ideas while the global is especially effective in producing and distributing status. Yet the global also opens up a wider world of ideas than does any national system, even that of the US. Global science exposes national science to the larger body of work while stimulating a continuous dynamism that is both collaborative and competitive, mimetic and innovative. It is more difficult to sustain original national work separately from the knowledge emerging elsewhere. Marginson (2018) discusses the global/national division of labour in the rapid evolution of science in China. A fruitful 'global/national synergy' was achieved by combining robust national system development, supported by policy centralisation, regulation and funding, with participation in global science. Internationalisation policy in China connected national science to the expanding global knowledge circuit, whose growth thereby helped to power national development of the scientific infrastructure. This global-national combination was possible because the national government provided scope for grass-roots initiative and open global connections, while scientists from the global system, especially the US, fashioned connections into science in China. The division of labour between global science and particular national systems is a feature of all national science. The idea of a division of labour suggests a sustainable global/national relation in which each needs the other, that plays out differently according to the strength and openness of national science.

Third, the global science system and the national science system are held together by people and institutions with multiple presences in the different scales, in the zone of multiple objects. Leading scientists play not just global and local roles but national ones. 'Scientific elites can play a mediating role in appeasing the tensions that emerge between national resources and international mainstream research' (Bornmann et al., 2018, 932). Highly mobile scientists are another key group. Migrant societies with extensive science networks harbour many people with multiple links and are key sites in these global/national conjunctions on an ongoing basis (Graf and Kalthaus, 2018, 2): for example, the US, Canada, UK, Switzerland, Singapore, Hong Kong SAR and Australia. Global cities exercise leadership nationally while also functioning as nodes in a global network (Maisonobe et al., 2016). Leading research universities are active both globally and nationally. Ahn et al. (2019), focusing on publication data from South Korea, identify 'bridging universities' within national science systems that exhibit high levels of degree centrality and play a leadership and mediating role in linking their domestic peers with world science. While few emerging and lower tier universities have the opportunity to network directly and extensively with leading foreign institutions (529-530), bridging universities can do so on their behalf.

Science is always both global-local and national-local. Individual agents and institutions vary in the extent to which the two identities or ways of seeing motivate their actions, but few are completely free of the intertwined ties of either. If the global system generates status that trumps national esteem, the stronger research nations often nurture major initiatives in knowledge building through their strength not of their science diplomacy so much as their political, economic, and institutional forms. Their communities of scientists, however internationalist in outlook, are also shaped by a national-cultural solidarity that they maintain when they are inside world conversations. The ongoing global-national balance suggests that the global-national relation is not a simple hierarchy, with the global on top, though it may so appear in small systems heavily dependent on the global. Wagner et al. (2017) remark: 'we do not see levels as in a hierarchy, but a continuum of interactions, feedback and exchange, suggesting a heterarchy of partially nested structures that may also be disciplining global connections but not constraining local choices' (1647).

***Tensions.*** Not all is bridges and synergies. The heterogeneity of the global and national systems means that a fault line can emerge. Does this happen?

In ‘The continuing growth of global cooperation in research: A conundrum for national governments’, Wagner et al. (2015) identify a potential tension between global and national. They are not sure how to understand the relation. On one hand global and national science are seen as interdependent and part of a common system: the relation is positive sum. ‘The international and national networks may be shaping each other in a process of co-evolution between the national institutional structure and the global network’ (Wagner et al., 2015, p. 11). On the other hand, on the same page the relation is discussed as zero-sum. The evolution of global system subtracts from national agency and activity:

> As international collaboration in science has grown, the role of the state in directing investment comes into question … international collaboration in science has risen dramatically over the past three decades, changing the landscape for scientific research in favour of global networks … growth of science is occurring to a disproportionate extent at the global level (Wagner et al., 2015, 11).

Wagner et al. (2015) understand the global/tension as inherent to the growth of global science and hence generally affecting all national governments. ‘We see the growth of international collaboration as decoupling from the goals of national science policies’ (, 2). This shares the perspective of Adams (2013), who argues that nations may lose control over their ‘scientific wealth either as intellectual property or as research talent’ (557). At the same time Wagner et al. (2015) also note that ‘the relative influences of national and international networks appear to vary among nations … the global system is highly influential for some countries’ (11) but not all. There is not one global/national tension in science, but many. Globality is nationally articulated. This is plausible but places in doubt the researchers’ larger generalisation about the displacement of national policy agency by global science. The researchers’ ambivalence (positive-sum? zero-sum? both?) is summarised by their statement that ‘the growth of the global network is an emerging organization added to (and possibly superseding) the national model’ (p. 11). Is the global system an add-on or a replacement or displacement for national science? It is clear the global system has become increasingly important. However, the data show that national co-authorship has also advanced. What is unclear is whether the growth of the autonomous global system *necessarily* diminishes the role of national agency in science.

This is difficult to pin down empirically, but Wagner et al. (2015) devise a method of assessing of the balance of power between the global science and national science systems. They ‘compare the international network to national networks in terms of distributions of institutional addresses… to what extent can the layer of internationally co-authored papers be considered a predictor of the domestic publication pattern at the level of a nation, or is the reverse arrow prevalent?’ (9). They find that in 34 out of 61 country cases, the international pattern of co-authored publications is a better predictor of the domestic pattern, than vice versa. But this method contradicts their own earlier understanding of the relation between national and global science. Leydesdorff and Wagner (2008) state that the two systems are not equivalent but heterogeneous (317): the global system is a decentralised network without unified agency; the national is a political-juridical-economic realm in which a single agent orders science. It is anomalous when Wagner et al. (2015) refer to science as a unity, as ‘an overall system (global and national)’ (12). It is one matter to compare national and global networks in terms of rates of growth, as in Figure 2; another to imagine them as equivalently causal. National and global science are not commensurate.

The issue is not so much that there is a ‘growing divide between international and domestic research’, or an ‘intellectual separation’ (Adams, 2013, 559), or that the goals of international collaboration have become ‘decoupled’ from national science (Wagner et al., 2015, 5). That is to underestimate the continued role of global scientists in national systems, and to attribute to collegial collaboration in science a larger causal power than it has. The point rather is that globally networked science is intrinsically beyond the control or even the ‘gaze’ of nation-states (King, 2011, 359). The domain of science that has slipped, not beyond the influence of national governments but beyond their full gaze and control, has grown. Does this impair national science as such? Perhaps it does not. National systems are primary in neither knowledge formation nor preferential attachment, but the role of national ordering in science was always elsewhere. Governments have never determined knowledge development as such, any more than they dictate decentralised messaging on the Internet. They may still gain enough from global science to make the national investment worthwhile, and not having advanced scientific capability close at hand is scarcely conceivable. Arguably, the global/national interface is not *generally* zero-sum as Wagner et al (2015) suggest.

This does not obviate the possibility of global/national conflict under particular circumstances. Lee and Haupt (2020) find that US-China conflict in science and technology has taken a normative form in competing notions of science. They describe an opposition between ‘scientific globalism’, grounded in a prima facie commitment to cross-border scientific collaboration as a global common good, and ‘scientific nationalism’, or ‘technological nationalism’, grounded in the belief that ‘nation states support, and seek to control, science and technology not to spur innovation for economic and social benefit itself, but for the state to harness the power of science to national advantage … in order to become relatively more powerful than rival nations’ (Cantwell, 2020, 11). Scientific globalism and scientific nationalism are incompatible and have very different implications for national policy. Arguably, multi-scalar science is associated with both sets of practices and effects (King, 2011). The efforts of US authorities to decouple US and Chinese science by shortening or cancelling the visas of Chinese researchers and students, discouraging collaborative schemes and blocking joint appointments, shows that strong nations can weaken connections in science and diminish combined discovery. In this way the global/national relation in science is rendered zero-sum. However, this global/national incompatibility does not flow from the evolution of knowledge networks as Wagner et al. (2015) imply but from the arbitrary intervention of political forces from outside science.

There is also tension between culturally hegemonic Euro-American centric global science, and national science systems in non-dominant countries, whose intellectual agendas and languages of use are marginalised, and outputs are belittled by the indicators in use (Chinchilla-Rodriguez, 2018a, 1486). However, the point again is that science in itself, and its fecund global growth, do not foster an inherent tension between national location and global cooperation. The problem lies not in the multi-scalar structure as such but in inequality and agency, in the relations of power articulated though that structure. In the US-China imbroglio, changes in the geo-politics, expressed as tension not just between nations but between national science systems, has turned what was a heterogeneous synergy between national and global science into decoupling and othering. If the US attempt at decoupling is successful, this outcome will be a fracture within global science, leading to either an engineered division into two global science systems, or a partial withdrawal of at least one of the two national science systems from global science – if that is possible.

### Implications for theory

The implications of the paper for social theory will be least understood but perhaps are the most important. The main implications are two-fold: (a) the heterogeneity of scales and the critique of scale invariance, and (b) material and perspectival multiplicity of scales, and multiplicity of objects. These factors taken together explain how two different sets of relations (the respective relations of global and national science) can become ordered on the basis of a stable coupling - without them being joined within a single system, or being paired dialectically, which would imply that they share an identity. To understand global/national science it is necessary to set aside the Aristotelian notion that each element or object in the world has a singular and fixed essence, distinct from the essence of all others (Hall and Ames 1987; 1995); and also to set aside the assumption from bibliometrics that all science can be represented in a single set of data, when the objects represented in those data are subject not to multiple meanings but merely to multiple classifications of single meanings. In bibliometrics scale can only be understood in terms of scale invariant qualities. Qualitative differences between scales are invisible. Yet that is what is important.

As noted, Appadurai (1996) contains a foolish prediction about the death of the nation-state. But it is a brilliant essay in other respects and has left its mark on a whole generation of social theorists. Earlier, the most influential argument was the notion of ‘scapes’ such as ‘ethnoscapes’, ‘financescapes’ and ‘technoscapes’ to explain different kinds of global cultural flow. But perhaps the larger importance of

Appadurai (1996) is his willingness to depart from bounded sets and linear cause-effect relations, while retaining notions of causal explanation. His scapes are partly open structures that can become combined in novel ways. Partly open structure expanded the reach of theory. In his 1978-79 lectures at the College de France, Foucault (2008) again expands the reach of theory by an unorthodox ontological move. Foucault muses on the problem of relations between heterogenous elements. He suggests that there is more than one way that objects can be joined. He poses an alternative to the dialectic, a dyad of heterogenous elements joined by a 'strategic logic'.

> A logic of strategy does not stress contradictory terms in a homogeneity that promises their resolution in a unity. The function of strategic logic is to establish possible connections between disparate terms which remain disparate (Foucault, 2008, 42).

Like Appadurai (1996) this idea of 'strategic logic' suggests partly open structures. Using Foucault's method, national science and global science do not have to be pushed into a single unitary system. Rather, the specific character of their multiple relations, overlaps, synergies and tensions can be explored. That is what this paper has set out to do.

Global science also calls up another kind of multiplicity. Science is now practised amid diverse paths to modernisation and multi-polarity in global relations. Jan Nederveen Pieterse (2018) remarks that 'the singular (as in capitalism, modernity) is appropriate to an era of universalism, an era in which a single centre or zone of influence dominates as lodestar' (p. 182). That era is fading. The rise of China and East Asia and a range of middle powers in both political economy and science is matched by the partial fragmentation of the old Euro-American hegemony; and the pluralisation of forms of political economy and political culture: state driven, social market or market driven. This in turn means that a more plural era 'theories and concepts become plural in a fundamental sense' (182). In national cases even the commonalities are context-shaped and a single template cannot apply.

> Key problems facing contemporary social theory are North-South thinking, rather than East-South; thinking in the singular, rather than the plural; scale inflation, or assuming that one level of analysis pertains across all levels; methodological nationalism; and the heterogeneity of capitalisms (Pieterse, 2018, 182).

Though it is widely recognised that persons have more than one identity at the same time (e.g. Sen, 1999b), multiplicity is under used in social theory. Though ‘diversity’ in its many manifestations is a central preoccupation of contemporary social thought, mostly this is variety observed through a singular lens. Multiplicity has more transformative potentials in the analysis of science under conditions of globalisation: multiplicity of scale and of scalar or national-cultural perspective; multiplicity of function, identity or meaning. As this paper has described, in science the same object, or phenomenon, or idea, may become included in more than one chain of activity, fulfil roles in more than one system synchronously, and serve more than one purpose. It may take more than one meaning. Rather than being part of a unitary set, or a dialectic, systems can be heterogeneous, different, while also sharing objects. Thus it is in science. Relations between global and national science are understood only by embracing the variety of heterogenous scales, and the multiple meanings of objects.

The last ontological notion is especially challenging. However, if the idea of social relationality is to be fully embraced, this *must* entail multiplicity. Relationality between wholly bordered objects is by definition impossible. Related objects must penetrate each other in part, must share the same space/time and do so without losing their otherness to each other. The insight is Heraclitan. Heraclitus’s point was that being is always becoming. Objects are always in motion and that means those objects are in more than one place. Parmenides and Zeno refuted Heraclitus with a ‘common sense’ refusal of the possibility of multiple location in space/time. As Appadurai shows, that refusal cannot resist the insistent pressure exerted by a swirling and changing reality that is fully exposed to the global. Singular space/time is a working hypothesis, a heroic simplification, utopian in its way, that makes scientometrics and other positivist science possible; but in knowledge-intensive fields in which ‘everything flows’ so readily it is difficult to hold for long. Correspondingly, related objects are both themselves and the other and these categories do not exclude each other. National science becoming global continues to be national. Not all that is national science is global science, not all that is global science is national, and the intersection is strategic.

Multiplicity also extends to multiplicity of lens, of perspective. A fuller understanding is gained by moving beyond the use of only one mode of vision and comparing, combining and integrating different perspectives (Sen, 2002), bringing more of the real world terrain into empirical view, while dethroning the powerful simplifications of unitary mathematisation. Scientometrics is suggestive but not definitive. Knowledge is both global and local in gestation; science and its relational networks are also episodically impacted by normative and financial power in the national and regional (EU) scales; science is shaped in institutions both locally and nationally nested; and science is sustained by persons who connect to every scale at the same time. Only when seeing all simultaneously is it possible to understand that science has become more local, more national and also more global.

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