

## RESEARCH PAPER

### The impossibility of the triple helix

David Emanuel Andersson<sup>1\*</sup> and Åke E Andersson<sup>2</sup>

<sup>1</sup> College of Management, National Sun Yat-sen University, Kaohsiung 80424, Taiwan

<sup>2</sup> Jönköping International Business School, Jönköping University, Jönköping, Sweden

#### ABSTRACT

A dynamic model that distinguishes between slow and fast processes shows that a triple helix model is impossible as a tool for promoting interdependencies among science, industry and government. We present a theorem to demonstrate that a triple helix strategy is logically impossible as a means of funding scientific research in universities. In spite of this logical impossibility, national and regional triple helix strategies to improve productivity and innovative capacity have been favoured by politicians of almost every ideological stripe. Coordination of science and industry by governments is not new; it harks back to the mercantilism of seventeenth-century Britain and France. In the twentieth and twenty-first centuries, triple helix policies have led to a short-term bias in favour of applied technological research. Several examples, ranging from the military use of scientists in world war II to Chinese high technology parks show how triple helix strategies tilt playing fields, suppress academic freedom, and expose scientists to the whims of politicians.

\*CONTACT: [davidemanuelandersson@cm.nsysu.edu.tw](mailto:davidemanuelandersson@cm.nsysu.edu.tw)

ACCEPTING EDITOR: Stuart Macdonald

#### Introduction

For more than a century, politicians and industrialists have been interested in universities not only as providers of higher education but also as producers of scientific research that countries and regions may harness as a key resource in their pursuit of various development goals. The political and industrial importance of science became especially evident during the buildup to world war II. A salient example is the Manhattan Project with the involvement of such scientists as Albert Einstein, Enrico Fermi and John von Neumann. After the war, several government-sponsored think tanks were set up in the United States with the intention

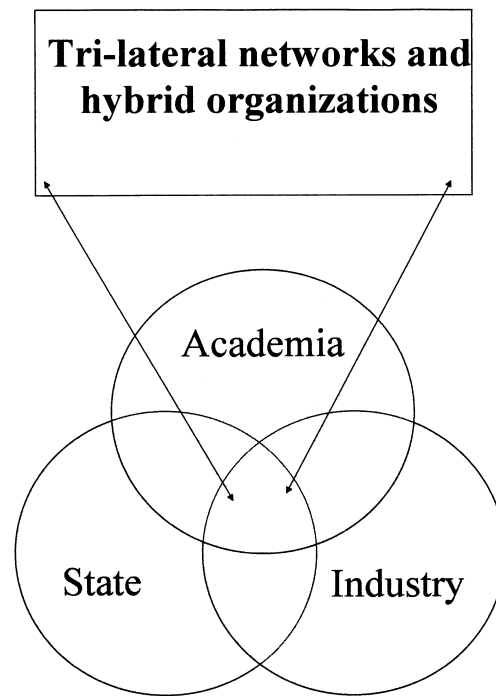
of forging closer co-ordination among industry, politics and science. The Rand corporation and the Cowles commission are two prominent examples. Recently, the European Union has advocated similar strategies of collaboration involving basic science, applied research and development (R&D) and innovation activities in different industries.

Many scientists at top universities, such as Oxford and Cambridge, have been sceptical of such partnerships. Engineers and economists at more technology-focused universities have typically been more responsive to three-part cooperation strategies, or what later became known as a 'triple helix'. The term is based on an evolutionary metaphor carried over from post-war genetics to inspire dynamic evolution towards increasingly competitive national or regional economies. Henry Etzkowitz and co-authors describe the triple helix as follows:

One model through which we can interpret these changes is that of the 'triple-helix.' A triple helix of university-industry-government relations transcends previous models of institutional relationships, whether laissez-faire or socialist, in which either the economy or polity predominated, with the knowledge sector playing a subsidiary role. The triple helix model attempts to account for a new configuration of institutional forces emerging within innovation systems, whether through the decline of the total state or the opening of the insular corporation. ... Different possible resolutions of the relations among the institutional spheres of university, industry, and government can help to generate alternative strategies for economic growth and social transformation. (Etzkowitz *et al.*, 2000, p.314)

Proponents of triple helix innovation policies often use Venn diagrams (such as the one in Figure 1) to illustrate the scope of interactions associated with the new program. This idea might seem new, but it actually resembles Schumpeter's view of economic development. Schumpeter (1934) claims that the ivory tower of science creates new theories and that innovative entrepreneurs are scavengers for useful theories they can use for profit-seeking innovations.

**Figure 1.** A triple helix of university-industry-government relations



*Source:* Etzkowitz and Leydesdorff (2000)

Leydesdorff (2018) explicitly refers to Schumpeter and evolutionary economics as theoretical building blocks in triple helix modelling approaches that may supplant the original, more institutional approach (*cf.* Etzkowitz and Leydesdorff, 1995). In the institutional model, innovators in the three sectors interact within an institutional structure that regulates their respective roles (Etzkowitz and Leydesdorff, 2000; Etzkowitz, 2002). The evolutionary model sees innovations as continuously affecting the relations among agents, such as scientific, industrial and governmental organizations. An endogenous innovative process leads to path-dependent reconstructions of relations so that the causal agent in one phase may become a dependent agent in a subsequent phase (Ivanova and Leydesdorff, 2014; Ivanova and Leydesdorff, 2015; Petersen *et al.*, 2016).

In spite of the apparent sophistication of the institutional and evolutionary triple helix modelling approaches, both fail to take account of timescale differences between science and faster-paced domains. Consequently, Leydesdorff claims that:

The TH [triple helix] was first defined in terms of links among universities, industries, and government(s) as institutional relations. However, an essential element of the TH thesis is that the relations among institutions have become knowledge-based and have therefore grown into a network. In this constellation, institutions can substitute for each other's functionality to a certain extent. Universities, for example, can take on

entrepreneurial roles (for example, by creating incubators and science parks), industry can organize academic education and research, and public-private relations between industry and government can be redefined in the light of new technological options. (Leydesdorff, 2018, p.5)

Proponents of triple helix strategies claim that greater coordination among universities, profit-seeking firms and government organizations can promote economic growth, knowledge-based development, and other political goals more effectively than when science, the market, and government remain three distinct domains of human interaction.

In this paper, we argue that triple helix strategies are subversive of science (including the arts and humanities) for four principal reasons. First, science evolves at a much slower pace than technological innovation or governmental objectives. Second, scientific discoveries are public goods in the sense of being non-rival in consumption and subject to high exclusion costs. The ideal is thus free diffusion of results rather than the quest for secrecy that often characterizes industrial and political actors. Third, the history of science demonstrates that scientific freedom of expression and problem formulation are associated with more scientific breakthroughs than dependence on externally-formulated research objectives (Polanyi, 1962; Hollingsworth, 2007). Finally, funding decisions that depend on commercial or political criteria are likely to be detrimental to research without obvious short-run commercial or political payoffs.

The importance of a long time horizon - reflecting the slow pace of change - as well as the importance of free diffusion and individual autonomy are not identical for all disciplines. Time horizons are longest in mathematics, philosophy, cognitive science, and basic natural science, but even faster-paced disciplines are not as myopic as industrialists or politicians preoccupied with quarterly earnings, annual reports, opinion polls and election results. Since knowledge is a public good, all disciplines are at risk when research may involve trade secrets or national security. Threats to scientists' individual autonomy will disproportionately affect fast-paced and technological disciplines with commercial or military applications. Conversely, lack of industrial or political interest may result in insufficient funding for the arts and humanities, social science, and basic natural science.

As we shall show below, triple helix strategies are not only undesirable from a scientific point of view, but also impossible if the goal is to align scientific results with commercial and

political objectives. The impossibility of science-industry-government alignment reflects differences in timescales. Even so, the triple helix strategy is much older than the term itself. Attempts to coordinate science, industry and government have occurred on numerous occasions since the 17<sup>th</sup> century. In pre-industrial Europe, an established church often circumscribed the activities of scientists, as became clear during the Renaissance. Isaac Newton avoided publishing some of his ideas because he feared censure from church leaders. But secular leaders were at the same time becoming increasingly interested in the application of scientific ideas to production; they wanted to influence science to promote their own power and prestige. An early advocate of an active triple helix strategy was the minister of finance under Louis XIV, Jean-Baptiste Colbert. Later dictators of powerful nation states, notably Joseph Stalin, Adolf Hitler and Xi Jinping, pursued neo-mercantilist triple helix strategies to their advantage.

In the liberal democracies of Western Europe and North America, triple helix strategies have become important as part of regional development strategy, as is attested by the growing number of science parks that are co-located with large engineering and business schools embedded in technology-focused universities. But regional triple helixes, such as the Research Triangle Park in North Carolina, are dwarfed - relative to the size of the world economy at the time - by national triple helixes of real or aspiring superpowers. The most quantitatively important example in the twentieth and twenty-first centuries is the military-industrial-scientific complex of the United States from world war II onward, as well as similar initiatives in the three great personal dictatorships of the modern era: the Soviet Union from the 1930s to the 1950s; Germany from the 1930s to 1945, and China in the 21<sup>st</sup> century.

Triple helix strategies have thus proven attractive to politicians, industrialists and applied researchers, regardless of political system. Scientists and scholars in more fundamental disciplines, such as mathematics, theoretical physics and philosophy, have as a rule been more resistant to the alleged charms of the triple helix.

### **Creative science and technological innovations - a difference in timescales**

Scientific creativity almost always precedes technological innovation. Technological innovations tend to occur as clustered outbursts, often decades or even centuries after the creation of the scientific foundations of these innovation clusters. A few examples of the

substantial delays between scientific breakthroughs and associated innovations should suffice.

The key early innovations of the Industrial Revolution depended on the scientific breakthroughs of Christiaan Huygens, Isaac Newton, Gottfried Wilhelm Leibniz and Leonard Euler (Puu, 2006). In the seventeenth century, lack of funding forced scientists to collaborate experimentally with engineers in transforming scientific findings into industrially useful objects. The twentieth-century innovations associated with peaceful and military uses of atomic power had to await several stages of scientific breakthrough. Carl Friedrich Gauss and Nikolai Lobachevsky provided the necessary mathematical foundations for later breakthroughs in the natural sciences, such as those of Albert Einstein, Marie Curie and Wilhelm Röntgen. A combined infrastructure of mathematical and scientific findings made later innovations in medicine, engineering and military technology feasible.

The current growth of information and communication technologies depends on the scientific foundation in computational mathematics that encompasses Isaac Newton, Leonhard Euler, Joseph-Louis Lagrange, Carl Friedrich Gauss and other mathematicians from the seventeenth to the twentieth century, as well as on the scientific breakthroughs of Alan Turing and John von Neumann in the 1930s and 1940s. Ever since the 1950s there has been a steady flow of mathematical and physical theorems that make it likely that new scientific theories will be uncovered in the twenty-first century. The new mathematics includes the key contributions of Henri Poincaré, Stephen Smale, Renee Thom, Edward Lorenz, Mitchell Feigenbaum, Benoit Mandelbrot and Hermann Haken. Leon Chua sums up the potential consequences for science and engineering:

Never in the annals of science and engineering has there been a phenomenon so ubiquitous, a paradigm so universal, or a discipline so multidisciplinary as that of chaos. Yet chaos represents only the tip of an awesome iceberg, for beneath it lies a much finer structure of immense complexity. (Chua quoted in Peitgen, Jürgens and Saupe, 1992, p.655)

The developing science of dynamic systems may have long-term impacts on fields such as cognitive science, artificial intelligence (AI), brain dynamics, neural networks, biomedical modelling, biochemistry and socio-economics. No policymaker could ever forecast the long-term importance of these changes. Hence, decisions on the size and allocation of funds

to these slowly and erratically developing fields will be arbitrary from a long-term cost-benefit perspective, regardless of how one defines net benefit.

Nonetheless, politicians of different ideological beliefs have concluded that the future comparative advantage or military strength of their polities depends on industrial and scientific research efforts. To be an important player in the triple helix has become a political priority from the continental or national level down to the individual region in many parts of the world. But there is a fundamental fact that no government or firm, no matter how rich or powerful, can avoid. It is that politics, entrepreneurial innovation, applied research, and scientific creativity are processes that operate on different timescales.

In the following section, we demonstrate how complications arising from differences in factors (such as relevant timescale, openness, uncertainty and cognitive distance) relate to the increasing complexity of scientific creativity. These factors imply a logical impossibility of planning dynamic interactivity between basic science and public policy as well as between basic science and most industrial research and development.

### **The impossibility of the dynamic triple helix**

Table 1 illustrates how the problems of different timescales and different spatial domains affect interactions among governments, profit-seeking firms and universities. As we shall demonstrate, these intrinsic contradictions make policies aiming at a stable and symmetric dynamic process impossible.

**Table 1.** Timescales and domains of triple helix components

<b>DOMAIN</b>	<b>TIMESCALE</b>	
	<b>FAST</b>	<b>SLOW</b>
<b>PRIVATE OR TERRITORIAL</b>	industrial R&D product innovation process innovation politics	military R&D pharmaceutical R&D
<b>PUBLIC AND GLOBAL</b>	statistics	creative science

	information mass media	scholarship art
--	---------------------------	--------------------

We now introduce a formal treatment of Table 1. Assume a dynamic system of  $N$  ordinary differential equations comprising two groups of equations. The first group consists of  $m$  fast equations, while the second group consists of  $m+1, \dots, N$  slow equations. In addition,

$x(i)$  = vector of industrial R&D, innovations and political variables for a given territory (nation or region); these are fast variables with effects that are private or territorially constrained

$g$  = a vector of slowly changing scientific models, theories, principles or paradigms.

A theorem by Tikhonov yields the system

$$dx(i)/dt = f(i)(x, g); i = 1, \dots, m \text{ (fast equations)}$$

(1)

$$\varepsilon dg(i)/dt = f(j)(x, g); j = m+1, \dots, N \text{ (slow equations)}$$

(2)

where  $\varepsilon$  is a number much smaller than 1 and greater than or equal to 0. Chaos is the generic solution if  $\varepsilon=1$  with non-linear equations (1) and (2). However, the time from the initial formulation of a scientific problem - via deductive reasoning and empirical hypothesis testing - to its final provisionally true solution determines the magnitude of  $\varepsilon$ . The variable  $\varepsilon$  is a decreasing function of the duration of analysing a scientific problem, a decreasing function of the complexity of scientific creativity, and an increasing function of global accessibility to scientific knowledge. With  $\varepsilon$  sufficiently small, the slow equations become approximately equal to zero:

$$f(j)(x, g) \approx 0 \quad j = m+1, \dots, N \text{ (slow equations)} \quad (3)$$

The set of fast and slow equations has a stable equilibrium solution under certain economically reasonable conditions:

**Theorem:** For each position of the slow subsystem, representing the slow dynamics of the sciences, the fast industrial R&D and political subsystems have plenty of time to stabilize. Such an approximation is called ‘adiabatic’ (see Tychonoff (Tikhonov), 1930; Haken, 1983; Sugakov, 1998; Wang, Peng and Jin, 2011).



**Proposition:** The theorem implies that the interactive system of applied R&D, innovation and politics cannot influence scientific creativity. Instead, industrial and political actors are subject to globally determined and given knowledge constraints inherited from earlier scientifically-creative periods. A planned triple helix process with dynamic interactions among industry, politics and science is thus impossible.

**Exception:** To the extent that a university, business or engineering school is run as a consultancy firm, three-part interaction close to a general equilibrium is possible because the  $\varepsilon$  for short-term applied research is similar to the timescale of industry R&D and politics. However, such applied activities are not consistent with the fundamental and long-term role of scientific knowledge as a global public good.

### **Science and innovation in the service of the nation - examples of triple helix policies in totalitarian and democratic states**

*L'État, c'est moi* (attributed to Louis XIV, but it could equally well have been attributed to Joseph Stalin, Adolf Hitler or Xi Jinping)

The most clear-cut early examples of how national innovation policies interfere in the activities of scientists are from seventeenth-century Britain and France. One example is the nationalist bias in the outcome of the collaboration between the French physicist Denis Papin and the German scientist Gottfried Wilhelm Leibniz on a prototype of the first steam engine. The royal society of London and the British parliament were unsupportive of this collaboration on British soil. The parliament finally awarded a monopoly to a British scientist/engineer.

Another early example of political interference in the world of science is the establishment and later transformations of the *académie royale des sciences de Paris* between 1666 and 1793. With a view to the potential economic benefits to the crown, the leading mercantilist, Colbert, initiated the *académie* in the king's private library in 1666. From there, science was to be supported as long as the gains would benefit the crown. By the eighteenth century, the national interest had come to regulate science and technological innovation; science was no longer the domain of independent scholars pursuing the public interest.

A counter movement against political interference in science occurred in the late seventeenth and early eighteenth centuries as part of the Scottish enlightenment in Edinburgh

and Glasgow, and later with the establishment of University College London in 1826. Also in the early nineteenth century, the German reformer and spokesman of the independent university, Wilhelm von Humboldt, advocated a separation of universities from industry and government. His principles were first applied to the University of Berlin (now the Humboldt University of Berlin) and later to other leading universities, particularly large German universities and American ivy league institutions, such as Harvard, Princeton and Yale. The political desire to control science and its innovative spin-offs has recurred many times since the seventeenth century. These initiatives span the political gamut from regions in federal democracies to the nation state in dictatorships. It was codified in the 1990s as the triple helix model of innovation (Etzkowitz and Leydesdorff, 1995).

### **National triple helix strategies in the 20<sup>th</sup> and 21<sup>st</sup> centuries**

There are, of course, differences between the formation of triple helixes of science, industry and government in personal dictatorships at one extreme and in liberal democracies at the other. In the totalitarian state, the dictates of the leader shape the long-run goals of both science and industry, whereas most scholarly treatments of the triple helix assume more pluralistic political systems of balanced interactions among semi-autonomous spheres. On the other hand, the triple helix strategy of a totalitarian state tends to be less susceptible to the reprioritizations and coalition-building attempts that occur over successive and sometimes overlapping electoral cycles. The Soviet Union and Germany in the 1930s and 1940s achieved an unprecedented level of coordination among the previously autonomous objectives of scientists, industrialists, and politicians. Twenty-first century China represents the third large-scale attempt to coordinate the three sectors in a leader-defined project of national rejuvenation. The American military-industrial-scientific complex after the end of world war II is an important example of the workings of the triple helix strategy in democracies.

#### *The Soviet Union*

Modern dictators with an interest in national greatness - as opposed to authoritarian leaders with a narrow focus on personal enrichment - have sought to direct and control scientific research and the industrial use of technology. One pertinent example is Stalin's attempt to thwart economic analyses that called into question his personal interpretation of Marxist-Leninist ideas. In 1939, the mathematician Leonid Kantorovich had formulated a

computable linear programming model of industrial production and resource allocation. This approach implied the use of shadow prices based on marginal costs; Stalin immediately attacked Kantorovich because marginal analysis was not consistent with *Das Kapital*. The publication of the model was delayed until 1956, three years after Stalin's death. In 1975, Kantorovich received the Nobel memorial prize in economic sciences for this contribution. In the central plans of the USSR, based on Marxian theory and historical materialism, nothing could occur by accident. The law of large numbers and the idea of random effects were decried as false theories, advanced by bourgeois mathematicians, such as Andrey Kolmogorov or Eugen Slutsky, who were forced for a long time to abandon statistical research.

The most well-documented case of political interference in Soviet science is the Lysenko tragedy. *Lysenkoism* was a political campaign against genetics and science-based agriculture that the agricultural scientist Trofim Lysenko pursued in collaboration with Soviet authorities. Stalin supported Lysenko's attacks on mainstream geneticists and ordered the persecution of at least 3,000 biologists, with several of them being executed on Lysenkoist grounds (Birstein, 2004). The party state supported only science that was consistent with official Marxism-Leninism and the industrial needs of the Soviet Union. Creative scientific work was assumed to be done in isolation from countries outside the Soviet Union, or - after world war II - outside the group of approved socialist states, such as Poland and Czechoslovakia. To ensure control, all science was organized in a hierarchical structure from Moscow to other regions, except for the separate structure of scientific work within the military.

#### *National socialist Germany*

The ideology of the national socialist German workers' party did not rest on any single scholarly source, such as *Das Kapital*. Instead it was based on the populist, anti-semitic agenda of *Mein Kampf*. This quote from *Mein Kampf* sums up Hitler's populist approach: "If you wish the sympathy of the broad masses, you must tell them the crudest and most stupid things" (Hitler, 1925, quoted in Hershman and Lieb, 1994, p.185).

Among German scientists the anti-semitic propaganda had started long before the formation of the national socialists. Two Nobel laureates in physics, Philipp Lenard and Johannes Stark, had been active before 1922 in the formulation of an Aryan physics strategy to diminish the importance in German universities of relativity theory and quantum physics

ruled by Jewish (especially Einstein) and ‘white Jewish (especially Heisenberg) physicists. When the Nazis needed quantum and relativity theorists, they abandoned Aryan scientists such as Lenard and Stark, and Heisenberg was pragmatically chosen to lead the scientific work on a German atom bomb.

After the Nazi takeover in 1933, there was a rapid transformation of the German economy into a military-industrial-scientific complex. The share of machinery and railway investments in the war-supporting industries grew from 49% of real per capita investment in 1933 to 77% in 1936, before reaching a peak of 86% in 1944 (Schermer, 2006). The Nazis focused on three scientific disciplines; they considered chemistry, physics/engineering and medicine to be of immediate utility for the war effort. A unified politics, science and industry complex was seen as the institution necessary for a victory of the Aryan nation state.

#### *China’s emerging triple helix strategy*

Unlike the Soviet Union or Nazi Germany, communist China had no rich scientific heritage that could be harnessed for political purposes. Imperial and Republican China had a Confucian heritage that valued education and scholarship, but only if they conformed to established truths as propagated by Confucius and his followers. There was no tradition of cultivating creative scientific breakthroughs, unlike in Germany and among the western-influenced elite of imperial Russia. China remained a continent of slow and sluggish growth, backward science and no industrial R&D.

The Deng Xiaoping regime’s pragmatic economic reforms after 1978 marked a new era of growth and structural change. The reforms consisted of parallel developments with significance for science. Not only were the universities reopened during the Deng era, but previously-banned Chinese cultural traditions were again tolerated, and in the case of Confucianism, celebrated. As late as the 1990s, however, Chinese science remained on the margins of global consciousness. Bibliometric work shows that output was still negligible before 2000 (Matthiessen *et al.*, 2000). The growth rate of science output may have been high, but from a low baseline.

Only after 2000 did the rest of the world start to take notice of science and innovation within China. Andersson *et al.* (2014) shows that the annual growth rate in the number of journal articles in science, medicine and engineering was more than twice that of official

economic growth for China from 2000 to 2010, which was the world's highest. Twenty-nine of the thirty fastest-growing large cities in terms of science output were in China, with Seoul being the only non-Chinese exception. Observations from global databases show a Chinese specialization profile resembling those of Japan and South Korea. Chinese science output has tended to avoid basic science, specializing primarily in engineering disciplines, with its greatest global share in nanotechnology research (Andersson *et al.*, 2013).

Andersson *et al.* (2014) shows that the spatial structure of Chinese science is more monocentric than that of other unitary nation states. Co-authorships involving scientists in different cities are strongly oriented towards Beijing, so that when scientists outside Beijing engage in long-distance collaboration, it is most likely that their co-authors are in Beijing. Beijing has evolved into the world's largest centre of science output since about 2010 - if output is measured as the total number of articles in journals indexed by the science citation index (SCI). Regional decomposition of research and development spending shows that Beijing, with a population of about 20 million, devotes a higher share of its gross regional product to research and development than any nation state of comparable size (measured as a share of its gross domestic product), and this includes high-spending countries, such as South Korea, Sweden and Switzerland.

In Beijing and in other major cities, such as Shanghai and Shenzhen, both national and sub-national governments have been active in promoting designated high-technology clusters with co-located private and state-controlled Chinese firms, joint ventures with foreign high technology investors, and national as well as regional universities and research institutes. The best known is Zhongguancun science park in suburban Beijing. The park involves the Chinese Academy of Sciences and China's two top-ranked universities (Peking University and Tsinghua University) as well as high technology spinoffs from these institutions (such as Lenovo) and non-Chinese initiatives (such as Microsoft Research Asia). Thus, Chinese policymakers have explicitly adopted models of government-science-industry cooperation that are in line with the triple helix model, and smaller versions of the massive Zhongguancun cluster have been replicated more than 80 times in other locations.

Despite its spectacular growth in quantitative terms, Chinese science exhibits several characteristics that reveal the underlying nationalist and autocratic impulses of post-Mao China. Among the world's 30 largest science agglomerations, Beijing and Shanghai have the

lowest shares of internationally co-authored articles, and article impact as measured by the mean number of citations are two of the three lowest (along with Seoul) (Andersson *et al.*, 2013). The Organization of Economic Cooperation and Development (OECD) recorded a very small share of less than 0.09 percent of GDP allocated to university-based science in China in 2007 (OECD, 2020). It has been growing since that year, but at a much slower pace than industrial R&D (see Table 2).

**Table 2.** R&D spending as a percentage of GDP, 2016 (2007=100)

<b>R&amp;D</b>	<b>United States</b>	<b>OECD</b>	<b>EU-28</b>	<b>China</b>
Industry	118	119	121	310
Universities	115	121	123	243
Difference	-3	+2	+2	-67

*Source:* OECD (2020)

While China’s triple helix strategy may prove successful in powering its growing military-industrial-trade complex, it is doubtful whether it will ever host scientific breakthroughs commensurate with its 18% population share or 15% share of economic output in 2019. Andersson (2011) explains how scientific breakthroughs have always occurred in great cities that are open to new ideas, allow the free dissemination of information, and are tolerant of ethnic, linguistic and religious minorities. This was as true of London in 1800 as it was of Vienna in 1900 and San Francisco in 2000. It is, however, as little true of Beijing in 2020 as of Berlin in 1933 and Moscow in 1930.

Until 2012, China would best be described in *de facto* terms as a pragmatic and authoritarian one-party state with economic growth the overriding goal of the political elite. Universities were formally subject to party supervision, but university party secretaries were often engaged in more privately profitable pursuits elsewhere. The description of China as a typical exponent of rent-seeking pragmatic authoritarianism is no longer valid. After the ascent of Xi Jinping in late 2012, the country has increasingly displayed all the signs of totalitarian dictatorship. China’s party and national constitutions incorporated a new leader-defined ideology, officially entitled ‘Xi Jinping thought on socialism with Chinese

characteristics for a new era'. Its most repeated catchphrases are 'national rejuvenation', 'the China dream' and the 'new era'. Xi Jinping advocates a highly interventionist approach to university governance:

Universities must be transformed into 'strongholds that adhere to party leadership' and political education should be made 'more appealing', the president [Xi Jinping] ordered, according to Xinhua, China's official news agency. ... Xi, a populist strongman who recently reaffirmed his political authority by being declared the party's 'core leader', said teachers needed to be both 'disseminators of advanced ideology' and 'staunch supporters of [party] governance'. Echoing a 1932 speech by Joseph Stalin the Chinese president told his audience teachers were 'engineers of the human soul' whose 'sacred mission' was to help students 'improve in ideological quality, political awareness, moral characteristics and humanistic quality'. (Phillips, 2016)

Such indoctrination is in the long run incompatible with attempts to internationalize scientific research and education pursued in the decade preceding Xi's rule. Hence it has become increasingly difficult for professors at Chinese universities to attend international conferences, and attempts to prevent people at universities and elsewhere from using virtual private networks to access independent sources of information have intensified. The following excerpt reveals how China increasingly prohibits the free dissemination of scholarly work:

The Chinese Communist Party is experienced in using various methods to coerce foreign companies and institutions into self-censorship, but its efforts were more overt and aggressive in 2017, particularly in the academic sphere. On August 18, Cambridge University Press (CUP) removed 315 articles from the journal *China Quarterly* from its China website without notifying the editorial staff. ... CUP reversed course just three days later following an international outcry, but in November, academic publisher Springer Nature shrugged off a *Financial Times* report on its decision to take down 1,000 articles for users in China, saying that "only one percent" of its content had been rendered inaccessible (Freedom House, 2018)

For purely political reasons, China is likely to suffer a self-inflicted creativity deficit in basic science, amplifying problems that have also affected many science parks in less restrictive parts of the world. We deem it likely that Xi-era China will converge to the totalitarian Hitler or Stalin models of the triple helix. But because of the initial backwardness of the Chinese economy, joint ventures involving foreign high-technology firms and Chinese state-owned enterprises will continue to play an important role as sources of state of the art technology.

*America's industrial-scientific complex*

Two persons with the same family name – Bush - are associated with major shifts in American views on the relationships among science, industry and politics. The earlier one - Vannevar Bush - was the major science policy adviser to president Franklin D. Roosevelt. At Roosevelt's request, Bush formulated a science strategy with the following introduction in 1945:

Progress in the war against disease depends upon a flow of new scientific knowledge. New products, new industries, and more jobs require continuous additions to knowledge of the laws of nature, and the application of that knowledge to practical purposes. Similarly, our defense against aggression demands new knowledge so that we can develop new and improved weapons. This essential, new knowledge can be obtained only through basic scientific research. Science can be effective in the national welfare only as a member of a team, whether the conditions be peace or war. But without scientific progress no amount of achievement in other directions can insure our health, prosperity, and security as a nation in the modern world. ... Therefore, I recommend that a new agency for these purposes be established. Such an agency should be composed of persons of broad interest and experience, having an understanding of the peculiarities of scientific research and scientific education. It should have stability of funds so that long-range programs may be undertaken. It should recognize that freedom of inquiry must be preserved and should leave internal control of policy, personnel, and the method and scope of research to the institutions in which it is carried on. It should be fully responsible to the president and through him to the congress for its program. (Bush, 1945, pp 1-4)

Bush's proposals were met with considerable expectation from American scientists. Later presidents, however, did not follow through. From Harry Truman onwards, America's political leaders wanted to influence science, mostly by imposing constraints of various types. For the most part, they saw universities as producers of useful human capital that could be deployed for industrial purposes. It rarely occurred to them that investments in the infrastructure of science could have substantial long-term payoffs. While most American politicians did not mind imposing eligibility constraints on how government research funds could be disbursed, they did not like being constrained themselves by scientific findings that imperilled their favoured projects. America's cold war politicians generally supported those scientists who were pursuing research programs with obvious military applications, and after the 1957 launch of the Soviet-made sputnik satellite, they also tended to support research that might enable America to overtake the Soviet Union in the space race. Many American politicians were sceptical of science without immediate military or technological benefits.



The most pronounced anti-science president was Richard Nixon. Nixon abolished the post of science advisor to the president, along with the president's science advisory committee. Nixon appointed an electrical engineer, Edward David, as his initial science advisor, but even this was too much scientific expertise. David had to leave and at the same time Nixon asked for the resignation of the assistant secretary for health, the surgeon general, and even the director of the national institutes of health.

Climatology and the environmental sciences have encountered economically-motivated political resistance since the 1980s from many politicians, particularly within the republican party. Other kinds of scientific research are resisted on religious grounds, as in the case of stem cell research. This type of resistance is less money-driven than the political resistance to climate change research, since it derives from the importance of the religious right as a voting bloc within the republican party. An analogous but less widespread resistance to genetic engineering - particularly genetically engineered food - exists within the democratic party, in this case because of the environmentalist voting bloc within that party.

The George W. Bush administration is a 21<sup>st</sup>-century example of resistance to science. The Bush administration "installed more than 100 top officials who were once lobbyists, attorneys or spokespeople for the industries they oversee" (Mulkern, 2004). At least twenty of these former industry advocates helped their agencies write, shape or push for policy shifts that benefited their former industries; "they knew which changes to make because they had pushed for them as industry advocates" (Mulkern, 2004).

Opposing these changes, the advocacy group Union of Concerned Scientists published a report on scientific Integrity in policymaking in 2004. Its authors claimed that:

A growing number of scientists, policy makers, and technical specialists both inside and outside the government allege that the current Bush administration has suppressed or distorted the scientific analyses of federal agencies to bring these results in line with administration policy. In addition, these experts contend that irregularities in the appointment of scientific advisors and advisory panels are threatening to upset the legally mandated balance of these bodies. ... There is a well-established pattern of suppression and distortion of scientific findings by high-ranking Bush administration political appointees across numerous federal agencies ... Incidents involve air pollutants, heat-trapping emissions, reproductive health, drug resistant bacteria, endangered species, forest health, and military intelligence. (Union of Concerned Scientists, 2004, pp.1-2)

A petition signed by more than 9,000 scientists, including 49 Nobel laureates and 63 national medal of science recipients, followed publication of the report. The petition stated:

When scientific knowledge has been found to be in conflict with its political goals, the administration has often manipulated the process through which science enters into its decisions. This has been done by placing people who are professionally unqualified or who have clear conflicts of interest in official posts and on scientific advisory committees; by disbanding existing advisory committees; by censoring and suppressing reports by the government's own scientists; and by simply not seeking independent scientific advice. Other administrations have, on occasion, engaged in such practices, but not so systematically nor on so wide a front. Furthermore, in advocating policies that are not scientifically sound, the administration has sometimes misrepresented scientific knowledge and misled the public about the implications of its policies. (Union of Concerned Scientists, 2008)

In response to such criticisms, Bush reversed his earlier views and actions in his state of the union address of 2006, pledging to promote scientific research and education to ensure American competitiveness in the world. He promised to “double the federal commitment to the most critical basic research programs in the physical sciences over the next 10 years. This work will support the work of America's most creative minds as they explore promising areas such as nanotechnology, supercomputing and alternative energy sources” (Bush quoted in Kalb, Peters and Wooley, 2007, p.1122). Bush's reversal is an illustration of how interactions among scientists, industrialists and politicians in a democracy resemble negotiation games, with unclear outcomes for the interested parties.

The American democratic system as applied to the national triple helix is a system built on interactions or negotiations among three spontaneous orders - science, democracy, and the market (diZerega, 2013). The co-evolution of these three orders generates aggregate science outcomes that no single individual could have predicted in advance. Democratic governments or competitive corporations may cultivate or neglect basic science, but they cannot dictate its outcomes. Dictators are no more able to dictate the results of basic science than elected and constitutionally constrained presidents such as George W. Bush. Still, the interrelationships among the three spheres are hierarchical rather than interactive in totalitarian countries, such as China. There is less bottom-up self-organization in science and markets in a state-capitalist dictatorship than in a liberal democracy, and none in the political sphere if the leader is always has to be right. Self-correcting feedback loops are therefore stunted in dictatorships, and they are intrinsically more fragile and prone to catastrophic errors (e.g., Mao's great leap forward) than even the most dysfunctional democracy. National

triple helix policies have been important in both democracies and dictatorships, but with very different designs and consequences. The unifying feature of triple helixes in all political systems and at all levels of spatial aggregation is that they are subject to an internal logical inconsistency that sooner or later causes them to crumble.

### **Regional triple helix strategies**

The most influential narrative about Silicon Valley focuses on Frederick Terman's early proposal to lease out some of Stanford's land under the name Stanford Industrial Park, later renamed Stanford Research Park. But based on several hundred interviews conducted in the late 1970s with influential Silicon Valley individuals, Macdonald (2016) concludes that the role of Terman, apart from his personal support for Bill Hewlett and David Packard, was a myth that served the interests of Stanford.

Stanford hardly figures at all in contemporary accounts of Silicon Valley's first decades. In as much as anyone had noted any information flow between Stanford and high technology firms, it was from industry to the university rather than vice versa. ... Few founders of Silicon Valley firms hailed from Stanford University; industry produced its own experts and entrepreneurs. Innovation in microelectronics was technology-led and often occurred in the absence of science. (Macdonald, 2016, p.555)

Silicon Valley was largely the spontaneous result of bottom-up entrepreneurship and networking. It nonetheless became the world's most important high technology cluster, with total employment of about 600,000 in 2017. Because the Stanford myth was so successful, it became the main inspiration for policymakers at the national, regional, and local levels. This is paradoxical. According to a 2017 Stanford University survey, Silicon Valley entrepreneurs tend to have an unexpectedly negative view of regulation, given their policy preferences in other areas:

Typically, individuals' views on regulation and redistribution correlate strongly; those with liberal views in the taxation and spending economic policy domains tend to have liberal views on regulation. ... However, stacking the technology and mass samples and estimating a regression of regulation attitudes on redistributive attitudes and a dummy for the technology sample reveals that technology entrepreneurs are 0.22 scale points (on the average rescaled 0-1 item) more opposed to regulation than one would expect on the basis of their views on redistribution ( $t = 20.68, p < 0.01$ ). ... Technology entrepreneurs are the only group to predominately select the option "The government should *not* tightly regulate business, and should tax the wealthy to fund social programs," with a majority selecting this option - nearly twice as many as any other group we surveyed. (Broockman, Ferenstein and Malhotra, 2017, pp.28-9)

Inspired by the apparent successes of Silicon Valley, Cambridge science park in the UK, and Route 128 in Massachusetts, regional policymakers rushed to create their own research parks, science parks and high technology industrial parks. The aim was to make their top regional university the cradle of high technology employment and regional economic growth. Manuel Castells and Peter Hall describe the typical approach in the 1980s and early 1990s, but the overall strategies have not changed much since then:

A hasty, hurried study by an opportunistic consultant was at hand to provide the magic formula: a small dose of venture capital, a university ... fiscal and institutional incentives to attract high-technology firms, and a degree of support for small business. All this, wrapped within the covers of a glossy brochure, and illustrated by a sylvan landscape with a futuristic name, would create the right conditions to out-perform the neighbourhoods, to become the locus of the new major global industrial centre. (Castells and Hall, 1994, p.8)

Growth in the number of science park has been high in most countries. Such parks are now a ubiquitous feature of advanced countries, as Table 3 shows. China has the most pronounced technology/science park orientation, with the rest of East Asia and the United States sharing this focus on short-term research, albeit to a lesser extent.

**Table 3.** Number of science parks, science park-SCI paper ratio, university research as share of GDP, R&D as share of GDP, and university R&D share, 2016

<b>Country</b>	<b>Science parks (number)</b>	<b>Science parks per 10,000 SCI papers (1996-2016)</b>	<b>University research spending: % of GDP</b>	<b>R&amp;D spending: % of GDP</b>	<b>University/total R&amp;D spending (%)</b>
----------------	-------------------------------	--	---	-----------------------------------	--

*Strong technology orientation*

China	82	1.8	0.10	2.07	4.8
South Korea	18	2.0	0.40	4.23	9.5
Taiwan	3	0.5	0.29	3.05	9.5
Japan	23	1.0	0.45	3.29	13.7

United States	72	0.7	0.39	2.74	14.2
Germany	13	0.5	0.51	2.93	17.4
Belgium	6	1.6	0.46	2.46	18.7

---

*Moderate technology orientation*

France	60	3.3	0.48	2.22	21.6
Switzerland	7	1.2	0.72	3.20	22.5
Austria	1	0.3	0.72	3.12	23.1
Australia	9	0.8	0.54	2.11	25.6
Italy	6	0.4	0.36	1.33	27.1
Finland	24	8.6	0.79	2.90	27.2
Sweden	12	2.2	0.90	3.28	27.4
Britain	63	2.2	0.48	1.66	28.9

---

*Mixed basic science/technology orientation*

Denmark	5	1.6	0.90	2.96	30.4
Spain	5	0.5	0.39	1.22	32.0
Norway	2	0.8	0.55	1.65	33.3
Netherlands	6	0.8	0.75	1.99	37.7
Canada	13	0.9	0.69	1.71	40.4

---

*Source:* OECD (2020); UNESCO (2020)

*Journal & Country Rank*

Castells and Hall (2004) conclude that there is meagre evidence that these regional political efforts have been successful when compared with Silicon Valley or Route 128, both of which evolved endogenously with very limited support from national or regional politicians. Evaluations of Swedish science parks have reached similar conclusions.

Dettwiler, Lindelöf and Löfsten (2006) analysed matched pairs comprising 134 on-park and 139 off-park Swedish firms in 1999. Their econometric study shows that patenting and product innovation differences between science-park firms and non-science-park firms are statistically insignificant. They also show that the level of interaction between the university

and firms located within science parks is low. Likewise, Ferguson and Olofsson's (2004) statistical analysis of Swedish science-park firms, using 1995 data, finds no significant revenue or employment differences between on-park and off-park firms. The major positive impact seems to have been the same as motivated the creation of Stanford industrial park after world war II - attaining a productive use of university land by stimulating startups and high technology employment opportunities for local university graduates.

### **How to pay for science**

The main producers of basic science are universities that adhere to principles associated with the Scottish enlightenment, the Humboldtian model of higher education, and the ideas of Vannevar Bush. Complementary with research universities are a handful of centres that provide key infrastructure for science, such as CERN and other hosts of expensive equipment. Four-year colleges, engineering departments and business schools are, with few exceptions, primarily producers of undergraduate and master's degrees. These institutions are valuable as suppliers of human capital for industry and government, but they often lack the human and material resources necessary for basic science.

If publishable scientific papers are the key research outputs of universities, then income from tuition fees can to a substantial extent fund the research of faculty members, although it is usually preferable if a diverse array of non-partisan and mutually independent research funds are available as a complement to tuition income. The national science foundation and the Rockefeller, McDonalds, Ford, and Wallenberg foundations are sources of such funds. The basic problem for the research universities is the lack of political understanding and interest in funding long-term scientific research. One example may suffice - the Swedish telecommunications company Ericsson spent US\$3.6 billion annually from 2012 to 2017 on R&D, a sum that approximately equalled all spending on university research in Sweden during the same period. As shown in Table 2, university-based research accounts for only about a quarter of total research spending in the OECD area. These observations indicate that interest in basic scientific research among politicians and industrialists is minimal.

The independence of research foundations and governmental science funding agencies is under threat to the extent that they give priority to 'impactful' research that supports national or regional triple-helix strategies. Many government foundations, particularly in Europe and East Asia, are heading in the direction of such short-term bias. One of many examples is the

research excellence framework (REF) in the United Kingdom, which explicitly expects ‘impact’ in addition to research quality (Stern, 2016). While the REF is less policy-driven and more transparent than the opaque National Natural Science Foundation of China, its 2016 review states that:

Impact is clearly one of the success stories of REF 2014, providing a rich picture of the variety and quality of the contribution that UK research has made across our society and economy. The resulting database of case studies is a unique and valuable source of information on the impact of UK research. Despite the high cost of the impact element (estimated at £55 million) evidence shows that it has contributed to an evolving culture of wider engagement, enhancing delivery of the benefits arising from research. (Stern, 2016, pp.21-2)

## **Final remarks**

The major output of universities is publicly accessible and creative scientific papers and books. However, the increasing involvement of politicians and industrialists in triple helix strategies has confused the basic mission of universities. This is evidenced by the relatively small proportion of national resources allocated to university research in most countries, with China as the most extreme instance. To increase their research activities, many universities have supported industrial research in science parks at the expense of basic science with its long time horizon. Another indicator of the loss of focus on the fundamental mission of universities is their increasing allocation of financial and human resources to administrative activities in marketing and other types of external engagement.

This paper argues that the triple helix is impossible because of unavoidable differences in the time scales and domains of the constituent processes. We make use of a theorem from the mathematics of dynamics to show that the interactions that triple helix strategies generate imply the logical impossibility of their aims, if science is understood as basic science with a long time horizon and strong publicness attributes.

## **References**

Andersson, Å. (2011) ‘Creative people need creative cities’ in Andersson, D, Andersson, Å. and Mellander, C. (eds) *Handbook of Creative Cities*,: Edward Elgar, Cheltenham, pp.14-55.

- Andersson, Å., Andersson, D., Matthiessen, C. (2013) *Öresundsregionen: Den Dynamiska Metropolen*, Dialogos, Stockholm.
- Andersson, D., Gunessee, S., Matthiessen, C. and Find, S. (2014) 'The geography of Chinese science', *Environment and Planning A*, 46, 12, pp.2950-71.
- Birstein, V. (2004) *The Perversion of Knowledge: The True Story of Soviet Science*, Westview Press, Boulder CO.
- Broockman, D., Ferenstein G. and Malhotra, N. (2017) *The Political Behavior of Wealthy Americans: Evidence from Technology Entrepreneurs*, working paper 3581, Stanford Graduate School of Business, Stanford University, Palo Alto CA.
- Bush, V. (1945) *Science - The Endless Frontier: A Report to the President*, United States Government Printing Office, Washington DC.
- Castells, M. and Hall P. (1994) *Technopoles of the World: The Making of Twenty-first-century Industrial Complexes*, Routledge, London.
- Dettwiler, P., Lindelöf, P., Löfsten, H. (2006) 'Utility of location: a comparative survey between small new technology-based firms located on and off science parks - implications for facilities management', *Technovation*, 26, 4, pp.506-17.
- diZerega, G. (2013) 'Outlining a new paradigm', *Cosmos + Taxis: Studies in Emergent Order and Organization*, 1, 1, pp.3-20.
- Etzkowitz, H. (2002) *MIT and the Rise of Entrepreneurial Science*, Routledge, London.
- Etzkowitz, H. and Leydesdorff L. (1995) 'The triple helix - university-industry-government relations: a laboratory for knowledge based economic development', *EASST Review*, 14, 1, pp.14-19.
- Etzkowitz, H. and Leydesdorff, L. (2000) 'The dynamics of innovation: from national systems and 'Mode 2' to a triple helix of university-industry-government relations', *Research Policy*, 29, pp.109-23.
- Etzkowitz, H., Webster, A., Gebhardt, C., Regina, B. and Terra, C. (2000) 'The future of the university and the university of the future: evolution of ivory tower to entrepreneurial paradigm', *Research Policy*, 29, pp.313-30.
- Ferguson, R. and Olofsson, C. (2004) 'Science parks and the development of NTBFs: location, survival and growth', *Journal of Technology Transfer*, 29, pp.5-17.
- Freedom House (2018) 'China media bulletin: 2017 year in review', 125, available at <https://freedomhouse.org/china-media/china-media-bulletin-2017-year-in-review-issue-no-125> (accessed February 2018).



- Haken, H. (1983) *Synergetics, an Introduction: Nonequilibrium Phase Transitions and Self-Organization in Physics, Chemistry, and Biology*, Springer, New York.
- Hershman, D. and Lieb, J. (1994) *A Brotherhood of Tyrants: Manic Depression and Absolute Power*, Prometheus Books, Amherst NY.
- Hitler, A. (1925) *Mein Kampf - Die Nationalsozialistische Bewegung*, Eher Verlag, Munich.
- Hollingsworth, J. (2007) High cognitive complexity and the making of major scientific discoveries' in Sales, A. and Fournier, M. (eds) *Knowledge, Communication & Creativity*, Sage, Thousand Oaks CA, pp.129-55.
- Ivanova, I. and Leydesdorff, L. (2014) 'Rotational symmetry and the transformation of innovation systems in a triple helix of university-industry-government relations', *Technological Forecasting and Social Change*, 86, pp.143-56.
- Ivanova, I. and Leydesdorff, L. (2015) 'Knowledge-generating efficiency in innovation systems: the acceleration of technological paradigm changes with increasing complexity', *Technological Forecasting and Social Change*, 96, pp.254-65.
- Kalb, D., Peters, G. and Wooley, J. (2007) *State of the Union: Presidential Rhetoric from Woodrow Wilson to George W. Bush*, CQ Press, Washington DC.
- Leydesdorff, L. (2018) 'Synergy in knowledge-based innovation systems at national and regional levels: the triple-helix model and the fourth industrial revolution', *Journal of Open Innovation: Technology, Markets, and Complexity*, 4, 16, pp.1-13.
- Macdonald, S. (2016) 'Milking the myth: innovation funding in theory and practice', *R&D Management*, 46, S2, pp.552-63.
- Matthiessen, C., Schwarz, A. and Find, S. (2000) 'Research gateways of the world: an analysis of networks based on bibliometric indicators' in Andersson, Å., Andersson, D. (eds) *Gateways to the Global Economy*, Edward Elgar, Cheltenham, pp.17-30.
- Mulkern, A. (2004) 'When advocates become regulators', *Denver Post*, 24 May, available at <http://www.rense.com/general53/wehn.htm> (accessed February 2018).
- OECD (2020) *Main Science and Technology Indicators*, available at [https://stats.oecd.org/Index.aspx?DataSetCode=MSTI\\_PUB](https://stats.oecd.org/Index.aspx?DataSetCode=MSTI_PUB) (accessed August 2020).
- Peitgen, H-O., Jürgens, H. and Saupe, D. (1992) *Chaos and Fractals: New Frontiers of Science*, Springer, Berlin.
- Petersen, A., Rotolo, D. and Leydesdorff, L. (2016) 'A triple helix model of medical innovations: supply, demand, and technological capabilities in terms of medical subject headings', *Research Policy*, 45, pp.666-81.

- Phillips, T. (2016) ‘Chinese universities must become Communist party ‘strongholds’, says Xi Jinping’, *Guardian*, 9 December 2016, available at <https://www.theguardian.com/world/2016/dec/09/china-universities-must-become-communist-party-strongholds-says-xi-jinping> (accessed February 2018).
- Polanyi, M. (1962) ‘The republic of science: its political and economic theory’, *Minerva*, 1, pp.54-74.
- Puu, T. (2006) *Arts, Sciences, and Economics*, Springer, Berlin.
- Scherner, J. (2006) *Industrial Investment in Nazi Germany: The Forgotten Wartime Boom*, University of Mannheim/Yale University seminar paper, available at <https://economics.yale.edu/sites/default/files/files/Workshops-Seminars/Economic-History/scherner-060329.pdf> (accessed August 2020), *mimeo*.
- Schumpeter, J. (1934) *The Theory of Economic Development*, Harvard University Press, Cambridge MA.
- Stern, Nicholas (2016) *Building on Success and Learning from Experience: An Independent Review of the Research Excellence Framework*, Department of Business, Energy and Industrial Strategy, London.
- Sugakov, V. (1998) *Lectures in Synergetics*, World Scientific, New York.
- Tychonoff, A. (1930) ‘Ueber die topologische Erweiterung von Räumen’, *Mathematische Annalen*, 102, 1, pp.544-61.
- UNESCO (2020) *Science Parks around the World*, available at <http://www.unesco.org/new/en/natural-sciences/science-technology/university-industry-partnerships/science-parks-around-the-world/> (accessed August 2020).
- Union of Concerned Scientists (2004) *Scientific Integrity in Policymaking: An Investigation into the Bush Administration’s Misuse of Science*, Union of Concerned Scientists, Cambridge MA.
- Union of Concerned Scientists (2008) ‘2004 Scientist statement on restoring scientific integrity to federal policymaking’, 13 July 2008, available at <https://www.ucsusa.org/our-work/center-science-and-democracy/promoting-scientific-integrity/scientists-sign-on-statement.html#.WnWbu6iWY2w> (accessed February 2018).
- Wang, K., Peng, J. and Jin, D. (2011) ‘A new development for the Tikhonov theorem in nonlinear singular perturbation systems’, *Nonlinear Analysis*, 74, pp.2869-79.