CHAPTER ONE

The New Invisible College Emerges

> If I am right about the flattening of the world, it will be remembered as one of those fundamental changes—like the rise of the nation-state or the Industrial Revolution—each of which, in its day . . . produced changes in the role of individuals, the role and form of governments, the way we innovated, the way we conducted business . . . the way science and research were conducted.
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> Thomas L. Friedman, *The World Is Flat*

Science—defined broadly as systematic knowledge about the natural world—offers humanity the promise of a better life. Scientific advances throughout history have helped save millions of people from disease, famine, and poverty. The discovery of penicillin, the development of high-yield seeds, and the distribution of electricity are but three examples of the ways in which science contributed to social welfare in the twentieth century. In many countries, such advances have had even more far-reaching effects by spurring economic growth and bolstering the creation of the large and vibrant middle class that many theorists believe is an essential precondition of democracy. Yet other countries have failed to reap similar benefits. Since the birth of modern science in the seventeenth century, gains in and application of scientific knowledge have been unevenly distributed, contributing to the widening gulf between the developed and developing worlds.[1] In this book, I seek to explain why that is so. I also examine how science is changing and how a new framework for the governance of science can help bridge the gap between the scientific haves and have-nots.

Thomas L. Friedman, *The World Is Flat: A Brief History of the Twenty-First Century* (New York: Farrar, Straus and Giroux, 2005).

As Thomas Friedman notes in the epigraph to this chapter, the organization of science is changing in fundamental ways. These changes are both less and more extensive than he suggests. Despite the accelerating diffusion of scientific data, information, and knowledge, the world of science remains far from flat. But its focus has changed from the national to the global level. Self-organizing networks that span the globe are the most notable feature of science today. These networks constitute an invisible college of researchers who collaborate not because they are told to but because they want to, who work together not because they share a laboratory or even a discipline but because they can offer each other complementary insight, knowledge, or skills.

These networks link scientists working in faraway countries through virtual ties. They also organize the constant physical churn of researchers around the world. They furnish the framework within which research teams form, mutate, dissolve, and reform, bringing together scientists from diverse backgrounds and sending them out again with new knowledge to share. In the twenty-first century melting pot of science, national citizenship or allegiance plays a minor role. Scientific curiosity and ambition are the principal forces at work in the new invisible college.

In contrast, scientific nationalism—in which countries view scientific knowledge as a national asset—was the dominant model of the twentieth century. National science ministries and policies funded and controlled scientific research to advance domestic goals, such as economic prosperity and military strength, and opportunities for collaboration were often constrained by national rivalries. This approach paid large dividends for those countries with the wealth, resources, and culture to invest in, retain, and build on a wide range of advances in knowledge. But it left many countries, which collectively represent the majority of the world's population, out in the cold.

The rise of the new invisible college creates challenges and opportunities to promote social welfare and economic growth. In particular, it gives developing countries a second chance to create strategies for tapping into the accumulated store of scientific knowledge and applying what they learn to local problems. This book seeks to lay the groundwork for such strategies by describing the new invisible college and explaining how it works. By applying insights gained from recent advances in network theory, I present a framework for understanding the organization of twenty-first century science.[2] I use a mix of quantitative and qualitative data to describe global networks and identify the rules that fuel their operation and growth. This information serves as a basis for discussing the policy challenges posed by the rise of networked science. Science policy can no longer be made based on national borders, even though nations still play an important role in promoting and regulating scientific activity. Because the structures that create knowledge are not contained within nations, they cannot be managed within national borders. New principles must guide policy now and into the future.

Origins of the New Invisible College

Even though today's invisible college is very much a twenty-first century phenomenon, it also represents the reemergence of an old idea. A review of history shows that the invisible college is not new to science—the same term was used to describe the group of like-minded independent scholars who first pioneered observation and experimentation to study nature in the seventeenth century. Science in those early days was the work of natural philosophers, usually those of independent means like Sir Isaac Newton and Irish chemist Robert Boyle. These individuals, who were largely free from government influence, shared information and insight in a universal language (Latin) without regard for disciplinary boundaries (which at the time barely existed). Then as now, networks characterized scientific organization and inquiry, with the early scientists corresponding and exchanging ideas as part of a common search for knowledge.

As the centuries passed, science progressed a long way from its roots. It became increasingly professionalized. Laboratories, such as those led by Pierre and Marie Curie, formed to focus on specialized subjects like biology, astronomy, physics, or medicine. A process of nationalization followed as nation-states consolidated in the nineteenth and twentieth centuries. Governments began to expand their authority over scientific activity by creating national scientific establishments, such as France's Centre National de la Recherche Scientifique (CNRS). Established in 1939, CNRS now manages more than 1,000 research groups across the country.

Strategic rivalries and fierce economic competition spurred similar and redundant investments in "big science" in other countries, particularly in the wake of the two world wars, which showcased the ability of science to bolster military strength. National governments grabbed hold of science and made vast investments in both military and civilian research establishments. Institutions like the U.S. National Science Foundation and the Russian Academy of Sciences invested heavily in the basic sciences. Sister agencies invested in high-profile projects—such as the race to the moon and the fight to find a cure for cancer—designed to cultivate an aura of national strength and prestige.

More recently, the structure of science has been changing yet again, with the rise of the new invisible college. Five forces that are driving the shift in the structure of science can help us understand this important development:

—**Networks.** Networks are made up of connections among scientists. The connections can exist within formal institutions or established projects, but they do not stop there. They are forged through meetings and common interests and extend across vast geographic distances. These networks are not designed or dictated by anyone, but neither are they random, and they operate according to underlying rules and dynamics that differ from those that have governed the organization of science since at least World War II. Armed with an understanding of these dynamics, policymakers will be better positioned to take advantage of the invisible college's strengths.

—**Emergence.** Networks among scientists emerge in response to new information, new connections, and new opportunities. Science is not a command-and-control system; it has more in common with an ecosystem than with a corporation. New ideas emerge from the combination and recombination of people and knowledge. Researchers with the freedom to identify the people and tools that can advance their work organize themselves into groups. Emergence, as a powerful force in knowledge creation, should be harnessed and nurtured in our networked era.

—**Circulation.** Brains circulate. Trained researchers move to places where they can maximize their access to resources and best contribute their talents to the pool of scientific knowledge. Knowledge and information also circulate. Unexpected connections arise from data placed on the Internet or otherwise shared among researchers. Researchers often do not even know that they will find a data set useful until they stumble across it in the well-known serendipity of scientific discovery. By promoting the circulation of people, information, and ideas beyond political borders, the invisible college can advance knowledge accumulation more effectively and efficiently than scientific nationalism.

—"**Stickiness.**" Place (location) still matters in science and innovation.[3] Despite the influence of the information revolution, face-to-face meetings remain essential. Beyond this, some sciences require large-scale, expensive equipment to advance research, making them sticky in comparison with other fields. Others require resources that are available only in certain locations. This stickiness promotes the geographic clustering or concentration of scientific activity. These clusters can become extremely productive because of the convergence of resources, people, and ideas. Clustering is an essential feature of the knowledge system, and even though scientific research is being distributed across the landscape, policy must also make room for specialization.

—**Distribution.** Once the realm of the lone genius, science is now a contact sport. Scientists and engineers around the globe increasingly see the benefits of coming together in teams that rely on distributed tasking.[4] Such collaboration is made possible by the vast growth in scientific capacity over the past century, as well as the growth of Internet-based technologies. The increased reliance on distributed tasking means that researchers no longer have to be in the same place as their collaborators, nor do they have to be in the same place as the problems they seek to solve. This trend toward distribution creates new opportunities for scientists and policymakers to access knowledge wherever it can be found.

A Burst of Discovery

Some of these forces and their effects are exemplified by a project called BeppoSAX.[5] Initially designed as a collaboration between Italian and Dutch astronomers to study the birth of the universe, this effort eventually brought together astronomers from around the world.

Gamma rays—bursts of light released when a star dies—are one of the most important sources of data on the nature of the universe's early moments. Before the inauguration of the BeppoSAX project, gamma rays were seen only rarely, on the chance occasions when they were caught by satellites whose primary mission was to scan the earth for unannounced nuclear bomb tests. The Explorer 11 satellite, launched in 1961, was the first to carry a gamma ray telescope. It picked up 22 gamma ray events in its four months of operation, offering a tantalizing glimpse of the additional data that might be collected by a satellite dedicated to this goal.[6]

In the early 1990s, a group of Italian astronomers at the Istituto di Astrofisica Spaziale e Fisica Cosmica di Roma launched a project to build a satellite devoted to scientific x-ray observation, independent of the spy mission of the Explorer satellites. The project quickly attracted international support with the participation of researchers at the Stichting Ruimte-Onderzoek Nederland (the Netherlands Institute for Space Research). As Marco Feroci of the Istituto di Astrofisica Spaziale observed:

> Making a satellite is very expensive, so you have to do the best job you can right from the start. To get the funds, you must convince the political powers that you are doing the best science. We had a team of Italian astronomers from all over Italy, but we needed expertise in the instrumentation. The Dutch were the best people doing this kind of instrumentation at the time we started our project, so we linked up with them.[7]

Several Italian and Dutch firms collaborated on the construction of the BeppoSAX satellite, which was launched in April 1996 and operated until April 2002.[8] In addition, the BeppoSAX team created a worldwide network of researchers to follow up on the data collected by the satellite. As Luigi Piro, the director of the BeppoSAX project science office, explained: "This experiment was designed from the beginning to be a network. Fifty observatories participated. This way, we could share data very quickly. Exactly as results came in as to the location [of a gamma ray event] we would send information to the e-mail network. Any person who had results or saw something could e-mail the others."[9] In this way, BeppoSAX operated as both a social network of researchers and a technical network using the Internet to link scientific equipment.

As the BeppoSAX team accumulated data on gamma ray events, its members became increasingly attractive collaborators to astronomers working on related questions. The researchers were soon overwhelmed with requests to coauthor papers. In deciding which requests to accept, Piro explained, the team relied on two factors:

> We looked at both quality of their data and their reputation. These are both basically the same. We went first to the highest reputation in the field because this basically guaranteed the quality of the data. We had data on gamma rays and other groups had complementary data on other wavelengths. We could not check all their data! So we depended on their good reputation to ensure that they had good data. We shared our information and they shared theirs and we gained a broader understanding of our results.[10]

He added, "As we worked with people from all over the world, we developed trust. It developed over time. This is what led to successful collaborations." These collaborations led to the publication of some 1,500 articles drawing on BeppoSAX data.[11]

This productivity was facilitated by the BeppoSAX team's unusual decision to make its data freely available to anyone. In the past, the Istituto di Astrofisica Spaziale—a government-funded institute—had sought to protect and secure any data it obtained. In the early stages of their project, however, Piro and his colleagues became convinced that open distribution was the best way to promote their own research. As Piro explained:

> We discussed this quite a bit in our team. We wanted to share data, but we weren't sure how to do this. A researcher has the right to explore his

> own instruments or research, but the entire community should also benefit. So we decided that we would waive our rights to have the data [on the location of gamma rays] to ourselves and in turn share them right away. This was not the standard practiced at that time. But it was a good decision because it allowed research that led to a harvest of data. As we shared, others shared with us, too.[12]

As this decision shows, the BeppoSAX team was picking up signals not just from gamma rays, but also from the transformation of science beyond the nation-state. Collaboration on providing equipment, reliance on a far-flung network, widespread distribution of data, the need for coordination, the value of openness—all are hallmarks of the new invisible college.

Early Reactions to the New Invisible College

The rise of self-organizing social networks among scientists, such as the BeppoSAX gamma ray team, is remapping science across the globe and changing the rules by which it is conducted. But in advanced countries, policymakers have been slow to grasp the importance of these networks. In the United States at the end of the 1990s, most policymakers were only vaguely aware of the global science system. Perhaps because of the enormous size of the U.S. science system, many saw little need to pay attention to the emerging global science and technology system. Others saw international science as an appendage of U.S. science. In an attempt to explain why U.S. science agencies did not need a global strategy, one congressional staffer commented, "International science is just foreign aid in another form."[13] Recommendations to U.S. agencies that they should take advantage of and nurture international scientific cooperation generated little interest. The U.S. Department of State's lack of attention to international science continued to be a topic of discussion at science policy meetings and among those involved in science advocacy, but the marriage of science and foreign policy remained an elusive partnership.

The European Union (EU) took a different approach. Beginning in the late 1990s, it sought to encourage cooperation in science among member states as part of its efforts to create a European Research Area (ERA).[14] Participants in a series of framework programs for research and technological development identified thematic priorities, such as broadband research or transportation, while making funding conditional on collaboration involving two or more EU countries. As a result, scientific collaboration grew rapidly in Europe. Little attention was devoted, however, to partnerships reaching beyond the EU's borders.

The inward-looking focus of the highly advanced scientific establishments did not go unchallenged. Calls from the United Nations and the World Bank to harness science for development became increasingly common in the 1990s, and programs were put in place to counter such phenomena as "brain drain" and the "digital divide"—terms that implied a win–lose structure to scientific knowledge. At the same time, other organizations focused on building scientific capacity within developing countries and encouraging links to research institutions in the developed world.

None of these policy approaches paid particularly large dividends. U.S. policymakers found themselves under increasing pressure to promote international scientific collaboration, and a great deal of diplomatic effort was expended to negotiate science and technology agreements. These agreements, though, had very little impact on the actual direction of cooperation. EU policymakers found that projects intended to strengthen the ERA often included non-EU members, which caused confusion about where the research benefits were accruing. Development agencies found that efforts to build science and technology capacity did not stick well in poor countries, and attempts to construct links between developed and developing countries presented difficult challenges.[15]

For the most part, efforts by developing country governments to imitate the infrastructure and investments of scientifically advanced nations have also failed, often because of flawed policy design. For example, many governments have created distinct policies for industry, for science, and for education, each designed to generate new knowledge or solve local problems, but with little cross-referencing among them. The policies are often written by three different ministries (usually communications, industry, and science/education) with minimal incentive to coordinate with one another. In addition, as part of their science and technology policy, many governments have established lists of priority areas for investment. Unfortunately, these lists tend to be generic, reflecting "hot" areas in global science—such as biochemistry, genetics, or nanomaterials—rather than an effort to link priority investments to local problems and issues. A similar lack of realism hampers many efforts to create national innovation systems. The plans themselves may be attractive, but they often have very little backing in the form of political will or budgetary allocations.

Even more important, these plans are typically ill conceived. For the most part, they propose to build a national system along twentieth-century lines, instead of reflecting the emerging system of science and technology that will be the environment within which nations must compete for talent, resources, and funds in the twenty-first century. Such efforts are doomed to fail because they neglect to account for the shift from a nationally centered scientific system to a global one in which researchers, not national authorities, set the rules. This shift presents new challenges for governments, who exercise less control over science than they did in the heyday of big science. But it also creates new opportunities, particularly for leaders in developing regions who sense the importance of the rise of the invisible college. Some policymakers are now turning away from creating national innovation systems and moving toward establishing knowledge systems that scan for knowledge globally and tie down knowledge locally. The shift is away from a focus on building institutions and toward a focus on the functions that further knowledge and adaptability.

The renewed influence of the networked model of science is very good news for developing countries in this sense—the global network is an open system that offers opportunities to new entrants, notably countries that did not actively participate in the system in the twentieth century. But the network is not transparent. It may operate by unwritten rules, but it operates by rules nonetheless, as well as by norms that are not controlled by any institution or government agency. No political official can promise membership in the new invisible college, but learning the rules, norms, and mechanisms that govern networks can improve policy outcomes.

Organization of This Book

To govern the emerging invisible college properly and extend its benefits to formerly excluded places and people, scientists and policymakers need to understand its principles. This book, then, focuses on describing and illustrating the five factors that are shaping the landscape of early twenty-first century science. Using theory and example, I make the case for a science policy that treats science and technology as an emergent networked system rather than as a national asset.

Part 1, "Rethinking Science and Technology as a Knowledge Network," reinterprets the organization of science as a set of emerging global networks instead of a set of nationally controlled institutions. Chapter 2 underlines the magnitude of this shift by describing the systems that evolved through history—systems that revolved around nations, not nature—and are now being left behind. Today, global scientific collaboration increasingly aims not to serve the interests of nations but the creation of knowledge. Although collaboration is spreading across all fields, it takes different forms in different disciplines. Four types of collaborative activity, each described in chapter 2, can be identified: coordinated, geotic, megascience, and distributed.

Chapter 3 identifies the factors and forces that drive the emerging structure of twenty-first century science, drawing from recent findings in physics, biology, and social theory. Increasingly science operates as a set of complex adaptive networks at the global level. These collaborative networks do not form randomly. They emerge from the choices of hundreds of individuals seeking to maximize their own welfare, and they exhibit identifiable regularities, much as markets do. Notably, weak ties, small worlds, redundancy, reciprocity, and preferential attachment interact to influence the pathways for the flow of knowledge as well as to shape the growth and evolution of networks. By understanding these forces, we can also learn how best to make use of the associated networks.

Part 2, "The Labyrinth of the World: Understanding Network Dynamics," details the dynamics of the new invisible college. Chapter 4 uses quantitative data to establish that global science does indeed operate like a network and that this network is growing at a spectacular rate. The chapter also explains how the network expands by focusing on the motivations that drive the individuals who constitute it. It shows that the pattern of collaboration in a wide range of disciplines follows the scale-free distribution that is characteristic of complex adaptive systems and explores the simple rules that generate such complexity. It also discusses the role of circulation in the new invisible college and investigates its implications for developing countries by focusing on the difference between "brain drain" and "brain gain."

Chapter 5 turns away from people to discuss the role of place in the invisible college. Even though new technologies make it possible to transcend geographic boundaries in a way that was almost unimaginable to previous generations, the geography of the invisible college is not entirely virtual. Place still matters. Chapter 5 shows why and suggests how that should affect our thought process about distributing scientific resources and devising strategies to more broadly diffuse their benefits. Science is currently highly concentrated in advanced countries, partly because of political support and partly because of the cumulative advantage of place. Such concentration can sometimes be advantageous and even necessary, but in other situations, distributed facilities or partnerships are more appropriate. Chapter 5 also suggests ways to redesign science policy to yield a more equitable distribution of the benefits of scientific knowledge. Finally, the chapter introduces the concept of a dual strategy that calls for both "sinking" of investments and "linking" to the global network.

Chapter 6 builds on this discussion by addressing the issues of scientific capacity and infrastructure, which are prerequisites for participating in the new invisible college. It defines capacity and analyzes the institutions and functions that constitute its essential underpinnings. It also considers alternatives to the model of scientific nationalism, which required each nation to build its own scientific infrastructure. Today, even though the core elements of scientific infrastructure must be available locally, they need not all be provided by the national government. Alternatives include sharing at the regional or international level.

Part 3, "Tapping Networks to Extend the Benefits of Science and Technology," places the findings about the global system into a governance framework. Chapter 7 presents policy recommendations for both advanced and developing countries. The chapter makes the case for a comprehensive science policy aimed at governing the new invisible college in a way that will more broadly disseminate its benefits to those formerly excluded from full participation. New mechanisms for supporting and using science will need to be crafted in response to this shift. And the skill of policymakers in crafting such strategies will largely determine who emerge as winners and losers from this period of complex change.

The new social structure of science poses significant, although divergent, challenges for both advanced and developing countries. Advanced countries will have to redefine their roles so that they no longer see themselves as "donors" but as participants in a global system. Developing countries have a unique opportunity to take advantage of the changing system by linking to the network and then tying knowledge down locally. Policies based on two key principles—open funding and open access—can help developing countries achieve these goals.

The tremendous influence of science on our global social and economic development raises the stakes for understanding its structure and dynamics. More than 50 years ago, science historian Herbert Butterfield predicted that the history of modern science would acquire an importance commensurate with anything that has come before in our study of the human condition. Science, he argued, "is going to be as important to us for the understanding of ourselves as Greco-Roman antiquity was for Europe during a period of over a thousand years."[16] The pace of change is so quick, however, that we cannot wait for historians to work it out. We must understand the system as it is unfolding, and that is the purpose of this book.

A Note about Methodology

I conducted research for this book over several years and employed both qualitative and quantitative methods.. The research proceeded from the broad to the specific—beginning with an analysis of the global network of science, moving to an examination of networks within disciplines of science, and then exploring the methods and motives of communication among individual scientists. Originally, one question drove the research: Why is international collaboration in science growing at such a spectacular rate?

I chose the methods for answering the original question for their ability to reveal the dynamics of interrelationships at the global level. The dynamics within any social network are difficult to measure, and global science is no exception to this rule. Communications reflect the dynamics of the global network, but they take place at different levels of formality and can be ephemeral.[17] As a result, this study focuses on activities of a more formal nature—those revealed in published articles—as opposed to conference participation, which is much less formal and of a shorter duration. For the most part, any scientific communication can be identified only by the traces it leaves behind (such as co-authored papers). In addition, only codified or published communications can be quantified.[18] But even though such data might represent no more than the tip of the iceberg of all scientific communications, they can be rich in information. For example, by identifying the home institutions of authors, we can show how knowledge production is increasingly distributed around the world. And because articles tend to report the results of successful communications, the overall study was biased toward collaborations that produced outcomes of enough substance to gain attention at the level of formal, peer-reviewed publications. All publications data were drawn from the Institute for Scientific Information (ISI) databases.

In addition to analyzing this type of quantitative data, I interviewed dozens of scientists and engineers who actively participate in global collaborations. Because I conducted interviews with those who are highly active in international collaboration, their stories reflect success in long-distance communication and networking. These interviews revealed some of the reasons that researchers choose to collaborate across geographical distances and across disciplines, as well as the challenges they face. The interview process shed light on why researchers study and work outside their home country. The interviews also yielded informative examples of how collaboration can create innovative approaches to research. I draw on these interviews at several points in the book to illustrate and amplify the conclusions generated by the data.