Chapter 2
The Dynamics of Scientific Knowledge: Macroscopic Views

Abstract Macroscopic theories of scientific change are holistic views of what drives the creation and acceptance of scientific knowledge. At the grand scale of scientific communities, such theories offer a conceptual framework for analyzing the development of a scientific discipline through philosophical, sociological, and problem solving perspectives. As mental models, however, these models of scientific processes are subject to pitfalls and biases that may hinder our analytic reasoning. Integrating theoretical and empirical studies has the potential to help us reach a new level of understanding the dynamics of scientific knowledge. Three major theories of scientific change are presented from philosophical, sociological, and problem-solving perspectives to highlight distinct concepts and expectations as well as shared characteristics.

Introduction

A complex adaptive system consists of numerous interconnected components. The state of the system as a whole may change due to a variety of reasons. Components can be added or removed, and their internal state and links to other components are also subject to modification changed internally. Perhaps the most widely known concept is the butterfly effect—small changes may cause large effects. A butterfly flapping its wings is usually considered a minor perturbation to the scale of any weather system. However, if such minor perturbations may cause magnificent effects later on, then we are dealing with a complex adaptive system.

There are many complex adaptive systems around us—forests, societies, and the growing body of scientific knowledge. A macroscopic view of a forest focuses on the ecosystem of a wide variety of individual trees, plants, and flowers that come with different shape, size, color, and growth patterns. A sociological perspective of the population focuses on relationships between individuals of different personalities and backgrounds. A philosophical view of science focuses on how different

C. Chen and M. Song, *Representing Scientific Knowledge*,
https://doi.org/10.1007/978-3-319-62543-0_2

disciplines of science create and organize their knowledge of the world, and what forces advance of scientific knowledge. These various perspectives share a deep interest in a complex adaptive system.

Is a tree falling down a minor event to a forest that would survive a threatening fire many years later? Is the publication of a scientific article a groundbreaking revolutionary event, or simply a minor perturbation to the growth of scientific knowledge as a whole? In this chapter, we set the platform of our analysis and discussions at a macroscopic level. Our primary focus is not only on the trees, but also the forest in which all the trees play a role. We will focus not only on individual researchers but also the groups and the communities in which individual researchers trailblaze their pathways and leave their footprints.

Mental Models

We borrow the idea of a mental model from psychology (e.g., Johnson-Laird 1983). A mental model is what we believe how a system operates or what is going on. For example, we may believe that the earth is the center of the universe. Given this mental model, we would be able to interpret what we see—galaxies further away from the earth seem to receding from us faster than galaxies nearby. In addition, we would be able to make predications on things that we have never seen. Many accidents occurred because of wrong mental models (Chen 2014). Individuals' mental models may differ due to social, organizational, cultural, and individual differences (Markus and Kitayama 1991). Mental models play critical roles in a wide variety of situations and activities such as situation awareness (Endsley 1995), intelligence analysis (Heuer 1999), creativity (Csikszentmihalyi 1996), discourse comprehension (Kintsch 1988), public understanding of science (Bostrom et al. 1994), and practice of law (Sutton 1994).

Easy to Form

Mental models are associated with a few very intriguing properties that may have profound implications on what we do or not to do with our own mental models. First of all, it doesn't take much of input for us to form our mental model. A glance may be all we need to generate a vivid and convincing mental model, or a story. We can fill up the details effortlessly with our imagination and with our prior experience and knowledge. Many cultures share a similar story: Someone had some of his properties missing and he started to suspect his neighbor. He decided that he would give a 'neighbor's watch' to his neighbor's behavior. The more closely he watched, the more seriously he was convinced: it must be him—it all fits! Before he got any chance to do anything about his neighbor, his properties were recovered but it had nothing to do with his neighbor. When he neighbor-watched his neighbor next day, he thought the neighbor didn't behave like a thief after all. He didn't bother to think what made him so convinced earlier on. This story explains why it is pointless to attempt to prove a hypothesis in science and why it is far more revealing to disprove a hypothesis.

The creation of our mental model is a very subjective process. It is influenced by our past experience, our education, cultural values, and expectations of others. We may unconsciously fill in the gaps by adding details that are not found anywhere in initial observations. Hallucinations and Pareidolia can be considered as extreme cases of mental models.

Pareidolia is an interesting psychological phenomenon in which one may see something in an image that does not exist. Widely known examples include seeing a human face on Mars in a 1976 image, seeing a female figure on Mars in a 2007 image, seeing Jesus and a number of celebrities in the Pillars of Creation, and seeing various objects in the Shroud of Turin. Sometimes amusing and creative sightings make entertaining news headings, whereas sometimes contradictory interpretations sustain lengthy debates between scientists with a substantial degree of domain expertise. In our 2014 book on the fitness of information, we have discussed the subjectivity of evidence in detail. It is important to bear in mind that our perspective is determined by our mental model. We can only see what our mind sees.

Designers may use various design metaphors to help the user to develop a mental model that would fit to a given design metaphor. For example, with a desktop metaphor, all our understanding of and experience with a desktop in the real world instantly become transferable and applicable. We can open a file. We can save a file. We can drag a file to the trashcan. We would be able to figure out how we are supposed to react to some of the actions even we haven't learned how to use them specifically. The greatest value of using a design metaphor is that we can save a lot of efforts in communicating various details. As long as we get the right mental model, we should be able to transfer a lot of our knowledge gained in one circumstance to another. The downside is obviously when a mental model departs from its original source, or its prototype, it is very hard for us to detect when two belief systems fail to match one another. When we just start to learn a foreign language, it may be difficult or inconvenient, but it is rarely dangerous. The most dangerous stage, however, arrives much later when we have convinced ourselves that we fully understand what is expressed in the foreign language. In other words, it is much easier for us to realize whether we understand something than whether we misunderstand anything. When we have a convincing and self-explained story, it would be much harder for us to even pay any attention and ourselves whether we get the story right in the first place. Stereotypes and prejudices are among some of the most common examples of a mental model that is formed too fast, especially when what we see is no more than the tip of an iceberg.

Hard to Change

The second property of a mental model is that it is hard to change. In the neighbor-watch story, additional observations reinforced the initial perception of a suspiciously behaving neighbor. Until he found his misplaced properties, the incorrect perception was reinforced incorrectly. Conclusive and undisputable evidence is essential to break the reinforcement loop. Intelligence analysis of the lack of evidence on Iraqi's mass destructive weapons resembles some of the issues discussed here. If we held a mental model that Iraq concealed mass destructive weapons, then Iraq's denial can only reinforce the belief. After all, if they were hiding the mass destructive weapons, of course they would deny the existence. The questions in such situations are not the answers to which would convince us our initial guess was right. Rather, a more valuable line of inquiry would question how we would know that our initial guess was not wrong.

The notion of diagnostic evidence is a key in making a decision in a complex and dynamic setting, especially when available information is incomplete, conflicting, or contradictory. Diagnostic evidence is the information that is capable of differentiating alternative interpretations and thus advancing the diagnostic process. A tuberculin skin test is a common test to see if someone has ever been exposed to tuberculosis (TB). If someone has ever been exposed to the TB bacteria, the skin test will see a firm red bump on the arm where a small amount of TB protein is injected under the skin. However, a positive skin test still cannot tell whether the infection is inactive (latent) or active (contagious). Thus, a skin test is not diagnostic if we need to know whether there is a risk for the TB to be passed to others.

Intelligence analysis has identified procedures that may help us to avoid some of the pitfalls and biases because of these properties of our mental models. For example, we are advised to brainstorm as many hypotheses as possible at the initial stage of investigation and refrain ourselves from diving into the evaluation of individual hypotheses. Evaluating a hypothesis would inevitably enrich the mental model that would justify the hypothesis with concrete and vivid details. We are particularly vulnerable to arguments that come with concrete and vivid details. "I know someone who was exactly in the same situation, …" and "Look, here is a photo to prove it." In general, we tend to believe what we see and it is easier for us to be convinced by specific details. A thorough brainstorm step earlier on in the process will help us to expand the horizon of our consideration because it will become increasingly hard to do so later in the process.

Once we have brainstormed as many hypotheses as possible, we need to eliminate hypotheses or the mental models that can be possibly disproved by the available evidence. Science is full of examples in which one question may have numerous possible answers. For example, 65 million years ago, at the K-T boundary, hundreds of species or even more became extinct within a relative short period of time, including dinosaurs that once seemed have dominated the earth. While the consequences are evident, what caused the massive extinction was far from clear. Researchers proposed as many as over 80 theories to explain what happened. Some theories direct our attention to forces from the inside of the earth such as massive and continuous flows of lava. Some theories draw our attention to forces from the deep space, including one-shot asteroid to periodical visits of astronomical objects orbiting around invisible stars. Many pieces of evidence are subject to alternative interpretations. The debates between scholars from different schools of thought or schools of beliefs lasted over a decade until diagnostic evidence was found in the Mexico Bay.

The best way and the most valuable way to validate a mental model is to challenge its very foundation with an alternative or competing mental model (Chen 2011, 2014). We use the term mental model, theory, and hypothesis exchangeably in this context. As researchers such as Randall Collins (1998) have studied in detail, the creativity typically arises from the intellectual confrontations of competing schools of thought. Collins noticed that great philosophers in history are likely to be the ones that fight for and defend their own schools of thought against the attacks of other schools of thought. The highest form of victory is not to defeat the opponent; rather, it is to accommodate the opponent in a higher level of order. In science, a powerful theory would adopt two contradictory theories as its special cases.

We know that the quality of our idea increases as we continue to come up with more ideas. In other words, we tend to generate increasingly better ideas. This is another reason that we should maintain a brainstorming process long enough to see good ideas. A scientific theory may not be formed as quickly as a mental model in our everyday life, but it shares some of the most fundamental properties of a mental model—any theory is a simplified and thus incomplete abstraction of the reality or the underlying phenomenon. Any abstraction may be locally accurate but globally wrong. Contradicting theories may not be good news to each individual theory, but holistically, it is likely to be the most valuable sign to these contradicting theories as a whole.

Theories of Scientific Change

We will introduce three accounts of scientific change from rather different perspectives. The first one is a philosophical theory of scientific revolutions from Kuhn (1962). The second one is a sociological theory of scientific change from Fuchs (1993a, b). The third one is an evolutionary theory of a generic problem solving process by Shneider (2009).

Scientific Revolutions

The central idea of Kuhn's theory is that science advances through a series of scientific revolutions. Each scientific revolution takes place when the predominant position of one paradigm is taken by a new paradigm. A paradigm is a view of the world, or a belief of what the world is and how it works. In other words, a paradigm is a mental model of the world shared by a community of scientists. As a mental model, a paradigm provides a basic framework for researchers to investigate a set of research questions with recognized methodologies.

Gestalt psychology believes that our mind is holistic. We see the entirety of an object before we attend to its parts. And the whole is greater than the sum of its parts. In terms of information theory, the way that individual parts form the whole gives us additional information about the system as a whole. In his *Patterns of Discovery*, Norwood Russell Hanson argues that what we see is influenced by our existing preconceptions (Hanson 1958).

Kuhn further developed the view how a *gestalt switch* is involved in scientific discovery and explained the nature of a paradigm shift in terms of a gestalt switch. Kuhn cited an experiment in which psychologists showed participants ordinary playing cards at brief exposures and demonstrated that our perceptions are influenced by our expectations. For example, it took much longer for participants to recognize unanticipated cards such as black hearts or red spades than recognize expected ones. Kuhn quoted one comment: “I can’t make the suit out, whatever it is. It didn’t even look like a card that time. I don’t know what color it is now or whether it’s a spade or heart. I’m not sure I even know what a spade looks like. My God!”

Paradigm Shift

A paradigm may go through a process that has the following stages: normal science, crises, and a paradigm shift, which defines a scientific revolution. At the normal science stage, the research in the field of study is well defined by the predominating paradigm. There is a consensus in terms of the kinds of research questions that should be investigated. Since the research agenda is set by the paradigm, research in this period is largely incremental as opposed to disruptive or revolutionary.

At the crisis stage, anomalies become inevitable and they challenge the very foundation of the currently predominating paradigm. Patchwork on the current paradigm is no longer adequate to resolve the crises. Researchers may propose drastically different paradigms to resolve the immediate crises. In addition, as the candidate of an alternative view of the world, the newly proposed paradigm should appear to have the potential at least as good as the current paradigm, although at this point, researchers would tolerate the lack of a thorough examination of the new paradigm because everyone knows it will take time to accomplish.

At the revolutionary stage, a critical mass has reached for the new paradigm to claim the predominant position from the once leading paradigm. Researchers in the scientific community start to re-examine the world through the perspective of the new paradigm. Once the new paradigm has established its predominant position, the science will repeat the process that the previous paradigm has gone through. One day there will be another crisis to emerge and challenge the foundation of the currently young and healthy paradigm. There will be another paradigm to emerge and take the leading position from the current paradigm. There will be an endless series of scientific revolutions.

The notion of paradigm shift has become a household name. Researchers from almost every discipline of science have embraced the idea. In the Web of Science, we have found as many as 567 variants of The Structure of Scientific Revolutions. One of the 567 variants alone has been cited 12,101 times. Among its numerous citing articles, 23 are in the category of highly cited articles in their own field.

Kuhn himself vividly described what we would expect to see in terms of citations. During the normal science, there should be a few highly cited groundbreaking articles that serve as exemplars of the predominating paradigm. Researchers routinely draw their inspirations from these groundbreaking articles. During a period of crisis, researchers are likely to cite articles that originally revealed the crisis. During the paradigm shift period, researchers are expected to cite the new paradigm.

Criticisms

Kuhn's paradigm shift theory has also drawn extensive criticisms to itself too. One is the suggestion that researchers on each side of competing paradigms may never fully understand the ideas of those on the other side. This is the famous incommensurability issue. Since each side has a mental model that is so different from its competing paradigms, a paradigm may make little sense to those who are occupied by different paradigms. It was believed that some of the hardcore beholders of a paradigm may never make that Gestalt switch and they may never adopt an incommensurable paradigm in their lifetime. Incommensurability refers to the communicative barrier between different paradigms; it can be taken as a challenge to the possibility of a rational evaluation of competing paradigms using external standards. If that was the case, the argument may lead to the irrationality of science.

Masterman (1970) examined Kuhn's discussion of the concept of paradigms and found that Kuhn's definitions of a paradigm can be separated into three categories:

1. Metaphysical paradigms, in which the crucial cognitive event is a new way of seeing, a myth, a metaphysical speculation
2. Sociological paradigms, in which the event is a universally recognized scientific achievement
3. Artefact or construct paradigms, in which the paradigm supplies a set of tools or instrumentation, a means for conducting research on a particular problem, a problem-solving device.

She emphasized that the third category is most suitable to Kuhn's view of scientific development. Scientific knowledge grows as a result of the invention of a puzzle-solving device that can be applied to a set of problems producing what Kuhn has described as “normal science.”

While we believe it is hard for one to see the world from different perspectives, we can all learn to see the world through a fresh perspective. The key is the information that is subject to multiple alternative interpretations. If multiple mental models hinge on such information, the hinges seem to be a good point to start. In fact, as we will see, Kuhn’s philosophical account and the sociological account that we will introduce next may appear to be incommensurable. Can we find a point that the two theories differ in their interpretations of the same thing we can all observe?

A common criticism of the notion of a Kuhnian paradigm shift is that it doesn’t seem to be fully consistent with the history of science. Some argued that Kuhnian revolutions are rare events. The Copernican revolution is a classic example of a paradigm shift. It marked the change from the geo-centric to the solar-centric view of our solar system. Another classic example is Einstein’s general relativity, which took over the authoritative place of Newtonian mechanics and became the new predominant paradigm in physics. How often are we experiencing scientific revolutions at the Kuhnian scale? When was the last time a scientific field was turned upside down?

A Kuhnian paradigm may correspond to a cluster of co-cited references, or a group of references that are frequently cited together. We can verify that distinct paradigms are behind different clusters of co-citations because of the conceptual frameworks they work with, which are determined by their paradigms. van Raan (1990) reported that co-citation clusters appear to be scale free. It means that there may be no such thing as a typical size of such clusters. In other words, a cluster of any size seems to be possible.

A domain of any size may be represented by a corresponding network. The dynamics of the domain can be largely characterized by the network, which can be further decomposed into clusters or specialties at a finer level of granularity. The notion of Kuhnian Gestalt Switch, i.e. paradigm shift, can be applied to each of these specialties as well as to the domain as a whole. Researchers in a particular specialty may work with their own paradigmatic research agenda. Some specialties may last longer than others, but they are all driven by a paradigm of their own, or a world view of their own. Researchers may remain in a specialty, if they continue to follow the same paradigm. In contrast, researchers may leave for a different specialty, if they want to branch off to a different paradigm. Thus, we believe that the process of scientific revolutions is not limited to rare and once-in-a-life-time revolutions. Rather, scientific revolutions take place all the time at different scales. For example, at a disciplinary level, computer science is relatively stable overall. However, at the level of one of its components, for example, artificial intelligence, it is inevitable to notice that a scientific revolution is taking place in at least in one area—neuro networks, notably, deep learning.

Explanation Coherence

Thagard (1992) noted although historians and philosophers of science have recognized the importance of scientific revolutions, there has been little detailed explanation of such changes. He proposed a computational approach to explain what he called conceptual revolutions with a special focus on how the conceptual structure changes in a scientific revolution.

He introduced the concept of explanation coherence of a theory and argued that the acceptance of a scientific theory is essentially due to its explanation coherence. Suppose we have two theories A and B. Both of them can explain the same set of phenomena, but theory A has fewer assumptions than theory B. In such situations, theory A is considered superior. Similarly, if two theories have the same number of assumptions, but one can explain more phenomena than another, the one with more explanation power is considered superior.

Thagard examined examples of scientific revolutions such as the conceptual development of plate tectonics in the latest geological revolution and Darwin's natural selection theory. A conceptual revolution may involve structural and non-structural changes. For example, the continental drift was transformed to modern theories through a structural change, whereas the change of the meaning of the evolution concept in Darwin's origins of species is non-structural.

Thagard suggests that we should focus on rules, or mechanisms, that govern how concepts are connected. For example, we should consider the variation of strengths of links over time. Adding a link between two concepts can be seen as strengthening an existing but possibly weak link between the two concepts. Removing an existing link can be seen as a result of a decay of its strength; they no longer have a strong enough presence in the system to be taken into account. Thagard identified nine steps to make conceptual changes:

1. Adding a new instance, for example that the blob in the distance is a whale.
2. Adding a new weak rule, for example that whales can be found in the Arctic Ocean.
3. Adding a strong rule that plays a frequent role in problem solving and explanation, for example that whales eat sardines.
4. Adding a new part-relation, also called decomposition.
5. Adding a new kind-relation, for example that a dolphin is a kind of whale.
6. Adding a new concept, for example narwhale.
7. Collapsing part of a kind-hierarchy, abandoning a previous distinction.
8. Recognizing hierarchies by branch jumping, that is, shifting a concept from one branch of a hierarchical tree to another.
9. Tree switching, that is, changing the organizing principle of a hierarchical tree.

Branch jumping and tree switching are much rare events associated with conceptual revolutions. Thagard examined seven scientific revolutions:

1. Copernicus' solar-centric system of the planets replacing the earth-centric theory of Ptolemy

2. Newtonian mechanics, synthesizing celestial and earth-bound physics, replacing the cosmological views of Descartes
3. Lavoisier's oxygen theory replacing the phlogiston theory of Stahl
4. Darwin's theory of evolution by natural selection replacing the prevailing view of divine creation of species
5. Einstein's theory of relativity replacing and absorbing Newtonian physics
6. Quantum theory replacing and absorbing Newtonian physics
7. The geological theory of plate tectonics that established the existence of continental drift

Thagard's central claim is that it is best to explain the growth of scientific knowledge in terms of *explanation coherence*. The power of a new paradigm must be assessed in terms of its strength in explaining phenomena coherently in comparison with existing paradigms. He demonstrated how the theory of *continental drift* gained its strength in terms of its explanation coherence.

Competition Leads to Scientific Change

Fuchs (1993a, b) proposed a sociological theory of scientific change after he criticized the Kuhnian paradigm shift as an oversimplification of the complex reality. Fuchs argues that advances of science are driven by sociological reasons. Scientists compete for recognition and reputation. Fuchs explains why a few types of scientific change may result from competitions when two factors interplay, namely mutual dependence and task uncertainty.

Mutual dependence refers to the social and organizational dependencies between scientists and their competing peers. Task uncertainty refers to the level of uncertainty involved in the course of scientific inquiry. The task uncertainty is high in scientific frontiers where research is essentially exploratory in nature and there is a high amount of tacit knowledge involved, for example, scientific discoveries of high creativity. In contrast, the task uncertainty is low in areas where tasks are routinized. A combination of high task uncertainty and high mutual dependence will lead to original scientific discoveries, which will bring a substantial degree of recognitions and reputations such as Nobel Prizes. A research area with intensified competitions is also likely to have a high retraction rate (Chen et al. 2013). A combination of low task uncertainty and high mutual dependence will result in specialization to maintain the tension between scientists with high mutual dependence while they work on routinized research.

According to Fuchs, Kuhn's theory does not account for the many possible reactions to perceived anomalies. Apart from switching to a different world view altogether, one can choose to ignore them, explain them away, try to accommodate them into established knowledge or make minor modifications of the theory. In the terminology of our mental models, one could choose to keep the existing mental model or ignore the anomalies. The question is what if anomalies are too prominent to ignore or too fundamental to patchwork the existing mental model.

Fuchs further attacked Kuhn's theory by arguing that Kuhn's theory expects only two basic types of scientific activity: normal science and revolutionary science. "Revolutions, however, are as rare in science as in other areas of society. Most scientific change appears to be nonrevolutionary." Fuchs quoted sociological studies that questioned the idea of sudden and holistic gestalt shifts. Instead, the sociological studies argued that even the few revolutions are dramatic culminations of a long series of smaller incremental changes and that the normal-revolutionary dichotomy in Kuhn's theory is too simple to provide an adequate account for the complexity of how science may change.

Fuchs proposed a sociological theory of scientific change named the Theory of Scientific Organization (TSO). His theory views scientific specialties as reputational work organizations in which material resources and social structures shape how scientists do research. A specialty is a group of researchers who have similar training, attending the same conferences, reading and citing the same set of literature. Specialties usually have a small core of highly productive and visible researchers, a semi-periphery of researchers with much less visibility, and a large periphery of inactive or transient researchers.

Fuchs' theory is built on three components: (1) liberal or conforming cognitive styles: how we think and what we perceive are shaped by social structure. Knowledge is social imagery because it reflects an underlying social organization. In a cohesive and homogeneous group, one is under pressure to conform to its cognitive standards. In contrast, loosely coupled and heterogeneous groups tend to have more liberal cognitive styles. (2) centralized or decentralized social structures: the nature of the work influences the social structures and cognitions of a group. Routine and predictable work is likely to emphasize formal rules, codified procedures, and administrative hierarchy. In contrast, uncertain, exploratory, and creative work is likely to have more informal, flexible, and decentralized social structure. (3) the materialist theory of consciousness: those who control instrumental resources and organizational facilities also control how ideas are generated.

Randall Collin's theory of the intellectual world (Collins 1998) and Richard Whitley's comparative typology of scientific fields (Whitley 1984) are two theories that have direct impact on TSO. Collins suggests that a specialty's structure is determined by two factors: how much scientists need to coordinate and how certain the research agenda is. Similarly, Whitley suggests two parameters: task uncertainty and mutual dependence between scientists. Physics, for example, has very high reputational autonomy and highly centralized resources. Researchers in such structures heavily depend on those who control reputations and resources. Task uncertainty is low because of the tight controls. In comparison, the mutual dependence between sociologists is low, while task uncertainty is high because of decentralized resources and a variety of options to gain reputations. Building on these concepts, Fuchs proposed to explain how and why various types of scientific change take place in various areas of science in terms of mutual dependence and task uncertainty as two organizational variables.

Table 2.1 Four categories of scientific change

		Task uncertainty	
		Low Routine, repetitive, predictable	*High* Information is incomplete, ambiguous, controversial, unpredictable
Mutual dependence	*Low* Loosely coupled networks, decentralized means of production	Stagnation	C: Fragmentation
	High Tightly coupled networks, concentrated means of production	B: Specialization Teaching and textbook writing, follow-up research; Competition is low	Permanent Discovery Research fronts, invisible colleges, highly competitive

The key idea is that competition drives change because scientists compete for attention, reputation, and resources. Scientists who are seen to advance the state of knowledge will receive the highest rewards. Thus competition drives scientists to produce novel findings. Nevertheless, the pressure to produce something new is not equally distributed in various areas of science. The core of Fuchs' theory is summarized in Table 2.1. The combinations of mutual dependence and task uncertainty define three major types of scientific change:

- Permanent Discovery
- Specialization
- Fragmentation
- Stagnation, or the lack of activity

Permanent Discovery

The most productive, most visible, and most impactful groups are research fronts or invisible colleges. The mutual dependence and task uncertainty are both high. These are the small and tightly coupled core groups of highly productive researchers. The task uncertainty is high as their work belongs to the frontiers of science. The competition here is the highest with a very short half-life of research papers. Since the research topics they are working on are so advanced, the members of the group cannot rely on published literature. Instead, they rely on the invisible colleges to maintain their leading positions. Small and Crane (1979) showed that this type dense and highly interactive research fronts are reflected in the scientific literature as highly interactive co-citation clusters. Due to the density of the network, changes happen in one part of the network will be quickly spread to the rest of the group. If there is one important lesson that we can learn from this type of scientific change, it is about how a discovery finds its way in the network. The significance of a discovery cannot be materialized until people start to pay attention to it. More importantly, the spread of a new discovery needs the attention from the leaders and members of the core; otherwise, the new discovery is unlikely to get very far.

Scientific knowledge at the research fronts has not reached the status of knowledge that is certain enough to be accepted by the research community. Research frontiers are areas where the uncertainty is the highest. There is no textbook that can teach us what is going on at research frontiers. This is the primary reason that one should stay in touch with the core group of the specialty to pursue the highly exploratory research.

Specialization

The sociology of science and scientific knowledge differentiates two types of science: (1) controversial, conflictual, and uncertain science and (2) objective, consensual, and authoritative science. The former is what is happening in science in the making, whereas the latter is after the research has settled and rationalized in hindsight. We will continue to discuss the topic of uncertainty of scientific knowledge later in the book. Uncertainty is an integral part of scientific inquiry.

Competition under the conditions of dense networks and low uncertainty of task will lead to specialization. Research that follows the specialization is very similar to the normal science stage in Kuhn's theory.

Specialization can be seen as an extension, refinement, application, or expansion of the pioneering work that has been done by researchers at the frontiers of the specialty. Fuchs described the tasks as "handed down" from the research fronts. The novelty is relatively low for doing routinized tasks. The prestige is relatively low and the competition is not as fierce as in research front groups.

Specialization is also seen as an option to create a shelter from fierce competition by branching off the core specialty and establishing an area where researchers may reduce the competition. A specialty's general pattern of growth and decline starts with a tentative and exploratory search at the beginning, followed by a period of fast growth and then a gradual decline. As the chance of making significant new discoveries is decreasing, the core scientists would leave the increasingly routinized area and search for new areas.

Fragmentation

The third type of scientific change is fragmentation. From a sociological point of view, natural sciences and social sciences differ because scientists and social scientists work in different organizational structures. The differences in the strengths and objectiveness of scientific statements are resulted from the type of networks they are in. The subject matter does not matter.

Social sciences and the humanities are soft because they have fewer, weaker, and more dispersed resources. “Strong and closely coupled organizations produce science; loosely coupled and textual organizations produce hermeneutics.” Because researchers are in a loosely coupled network, their work is unlikely to travel far and wide as quickly as researchers in a tightly coupled network. The high uncertainty associated their tasks means that it is generally difficult to determine the significance of change and obtain a sense of direction in which such changes may direct. Thus scientific change under such conditions would be mostly unstructured with an unclear direction or sense of progress.

Fuchs’ theory attempts to explain scientific change from a sociological perspective. Its central premise is that competition leads to scientific change. A specialty starts with a tightly coupled core group of scientists. The most innovative and advanced research is likely to appear in this part of the specialty. The research fronts laid down the groundwork, which would typically lower the uncertainty and probably the cost of accomplishing similar tasks in new areas. As a result, specialization becomes an attractive option. Scientists carve out an area where they can routinize highly special procedures with increased sophistications to shield their professions from external competitions. Specialized research becomes highly productive. In both of the research fronts and specialized areas, scientists belong to tightly coupled networks. The competition would be considerably weaker in loosely coupled networks, where researchers have more controls of what they do. The task uncertainty divides researchers who are in loosely coupled networks further: those with high task uncertainty and those with low task uncertainty. Task uncertainty in this context reflects whether the research in question is creative and original or codified and trivial. The former leads to fragmentation. The latter leads to stagnation.

What do the theories from Kuhn and Fuchs have in common? How do they differ? Are they describing the same phenomenon from different perspectives or the two sides of the same coin? Are these two mental models compatible?

Kuhn’s normal science and Fuchs’ specialization share many similarities. Researchers in both cases have an established framework to pursue their research. For Kuhn, the stability is provided by the predominant paradigm. For Fuchs, the routinization is resulted from the pioneering work of the research fronts.

Research frontiers in Fuchs’ theory are the most creative, volatile, and uncertain stage of a specialty’s growth. In Kuhn’s theory, the most creative and unpredictable stage is when the currently predominating paradigm is in crisis. A philosophical point of view may not pay much attention to sociological parameters of researchers behind such crises. Who would be the one to draw our attention to anomalies, researchers in an area of specialization or researchers from the research fronts of a specialty? By the time a paradigm may encounter a threatening crisis, pioneers in the original core of the paradigm have probably already moved on. In Kuhn’s theory, researchers may switch to a new paradigm as a scientific revolution. From a sociological point of view, researchers may have many choices in response to crises. There may be pragmatic reasons. For example, if established researchers were to switch to a new paradigm, it is likely that they will have to throw away a lot of domain expertise that they have earned in a hard way.

An Evolutionary Model

A relatively new theory of the evolution of a scientific discipline is proposed by Shneider (2009). He suggests that his theory complements existing theories of scientific process, including Kuhn's structure of scientific revolutions. He devoted much of his attention to the characteristics of scientists that would be most influential and productive at each stage.

Stage I—Conceptualization

The evolution of a scientific discipline has four stages. At the first stage, scientists introduce a new language to describe a new subject matter. To Isaac Newton, the new language was differential equations and the new subject matter was mechanical movements. To Antoine Lavoisier, the new language was chemical equations and the new subject matter is chemistry as we know it today.

Scientists working at the first stage may not be the ones who discover new facts. Lavoisier, for example, did not discover any substances. Nor did he invent any chemical apparatus. However, the new language created by Lavoisier connected many previously isolated pieces together. Watson and Crick are another example of first-stage scientists. They discovered the double helix structure of DNA.

First-stage scientists would focus on essentials and tolerate the uncertainties in many other aspects. According to Shneider, "What might be considered to be incompleteness and inaccuracy is, in reality, the formation of a first-stage hypothesis." Shneider further elaborated the point using Dmitry Mendeleyev as an example. Mendeleyev created the periodic table. He reserved positions on his periodic table for elements that ought to exist but yet to be discovered.

Shneider characterizes first-stage scientists as those with a broad range of interest who tend to make contributions across different fields of science. First-stage scientists have strong confidence and they are able to sustain criticisms from the most reputable colleagues. They are good at making use of philosophical, esthetic and culture perspectives. They are able to connect seemingly unrelated topics to make their arguments. Finally, the most critical trait of first-stage scientists is their ability to generate interests in their ideas and sustain them into the second stage.

Taken together, the most unique defining characteristic of first-stage scientists is their outstanding vision. They are able to see profound connections or properties that others cannot see. Shneider emphasized the role of introducing a new language in the emergence of a new scientific field. Perhaps a more intuitive way to clarify this is to ask what the new language could convey that other existing languages could not. What do the double helix and Mendeleyev's periodic table have in common?

Stage II—Tool Building

The second stage of the evolutionary model is critical for the development of research methods and tools. The value of the instruments developed at the second stage will be ultimately determined by how much they will be used at the next stage. The importance of method is evident in recognitions made by prestigious awards such as Nobel Prize awards. Method papers are among the most cited types of publications. Many powerful research tools typically have their user populations ranging across a wide variety of scientific disciplines. A stage-two field is probably the easiest one to identify. One can check how many tools have been developed and used within a relatively short period of time, for example, within a five-year interval. The basic local alignment search tool (BLAST), for example, is one of the most highly cited papers.

Stage III—Applications of Tools

The third stage of the evolution is characterized by the application of established research methods to new targets. This is the most productive stage in terms of the data and new knowledge. It is not really whether the new target area is ready to accept new methods from their generous provider. Rather, it is whether the research field as the provider has reached its third stage. This realization may have practical implications. Instead of searching for potentially useful techniques in all scientific fields, one only needs to search for them in stage-three disciplines or fields.

Anomalies are most likely to rise at the third stage. The research at the third stage is probably stretched as far away as possible from the original ideas proposed in the first stage. The discrepancies between the source field and the target field may become apparent. Similarly to Kuhn's theory, one way to handle the anomalies is to switch to a new world view. Third-stage scientists are probably application oriented. They believe that a new theory would be useless unless it can solve concrete problems. First-stage scientists, in contrast, are generally less concerned about finding immediate applications for a potentially valuable theory. They are less likely to be bothered by the lack of clear indications of future applications. This type of research is sometimes referred to as basic research as opposed to applied research. Research conducted by the TRACES project found the duration between the initial basic research and the first clear application can last for 50 years and most likely much longer. If future first-stage scientists try to create the first stage of a new field, they may face the resistance from the current third-stage scientists.

Stage IV—Knowledge Codification

The fourth evolutionary stage is marked by a relatively low productivity of new knowledge. Research activities in the fourth stage become increasingly routinized. In addition, the skills and knowledge learned through the first three stages need to be passed on to next generations. Like first-stage scientists, fourth-stage scientists need to provide a holistic view of their discipline. Unlike first stagers, fourth stagers are good at understanding facts and they follow the latest developments. With their complementary strengths, they are the best helper for would-be first stagers to branch off from a stage-three field.

From a more pragmatic point of view, a grant proposal may benefit from a variety of reviewers from scientists who have strengths associated with different stages of scientific disciplines. Perhaps it would make an interesting exercise to look at the evolution of your own field of research. Can you find who the first-stagers are? Who might be second-, third-, or fourth-stagers?

Multiple Perspectives

There are other theories of scientific change (Mulkay 1975). For example, a transition model of Exploration → Unification → Decline/Displacement was proposed by Mulkay et al. (1975). Nevertheless, the theories outlined above are representative. They cover the major characteristics of the development of a scientific field.

These theories evidently overlap. Kuhn's competing paradigms, Fuchs' research fronts, and Shneider's first stagers all represent the initial conceptualization of a new research framework. Shneider's tool building second stagers and Fuchs' specialization in high dependency and low task uncertainty share common features of routinization and codified knowledge. Shneider's third-stage scientists who apply proven techniques to new targets may expand the scope of a field uneventfully or trigger anomalies that may take much more creativity to handle. This division may roughly correspond to Fuchs' classification of task uncertainty. Fuchs played down the chance of a profound scientific revolution. Instead, he drew our attention to the small and gradual changes that eventually build up.

Shneider's first stagers are most likely the members of the invisible colleges or the core groups of research fronts in Fuchs' theory. Shneider's second stagers, tool builders or methodologists, are likely to be associated with Fuchs' specialization. At least some of Shneider's third stagers may become the research fronts of a new field. From Kuhn's point of view, researchers who are most likely to introduce a new paradigm would be those who are visionary pioneers with a broad range of interest across different fields or specialties.

Kuhn's theory is philosophical in nature and focuses on the forest of scientific knowledge. Kuhn's mechanism of change is very clear—a Gestalt switch in response to irreconcilable anomalies. Fuchs' theory offers sociological explanations to scientific change. Fuchs does not accept a sudden revolutionary change such as Kuhnian paradigm shifts. Instead, Fuchs believes that competition for recognition and reputation leads to scientific change. Fuchs provided more details to explain the types of change may be resulted from an interaction between mutual dependence and task uncertainty. To Fuchs, the most likely source of scientific change is the research fronts or a small core of highly creative people. Scientific change boils down to whether one can attract people's attention and for how long. Having something new to say is one way and probably the most effective way to do it. As we can see from another sociological theory—That's interesting!—the best way to get our attention is to challenge what we believe. If we know our audience believes that the earth is the center of the universe, then we would probably get their full attention if we tell them that the earth is out the center of the universe. Similarly, if we believe that there is only one universe, then we would probably be very eager to find out more if our physicist tells that there are in fact multiple universes—multiverse! How come we haven't seen any signs of any other universes for all these years?

Shneider's theory is probably the most complicated among the three theories. Scientists at each stage are mostly profiled by concrete examples rather than declarative definitions. Few of those characterizations are unique. The problem solving plot is probably the most valuable contribution of Shneider's theory. The problem is identified. Tools are developed to solve the problem. Then we apply the tools to new targets, which are likely to trigger new problems. For those who have a holistic vision, they would document the process and what we have learned along the way. The problem solving framework provides a template for us to interpret the growth of a research area that is so generic that it seems to be applicable to many scientific domains. On the other hand, does BLAST alone sustain a field of research? Do other scientists put their work on hold while tool builders construct new instruments? Similarly, when third-stagers enjoy finding new targets, what would other stagers be doing? We are unlikely to find answers to these questions unless we examine the evolution of several scientific domains in detail. We believe thorough cross-examinations of scientific fields should be done to answer these questions. To our best knowledge such studies of multiple fields across multiple theoretical frameworks are currently missing.

Summary

The macroscopic theories of scientific change introduced in this chapter provide a conceptual framework for the study of the dynamics of scientific knowledge. By presenting these theories with distinct perspectives side by side, we hope that their similarities and differences are made clear. We also need to bear in mind that, as mental models of scientific disciplines, these theories provide a valuable reference for the development and validation of computational approaches to the study of scientific knowledge. It may well be true that science advances through all the possible routes described by these theories collectively in that there are indeed paradigm shifts taking place, scientists do actually compete for their recognition, and applications of special-purpose tools really lead us to new discoveries. The collective value of these theories is that they are insightful and inspirational for us to characterize something as complex, dynamic, and abstract as the knowledge of sciences.

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http://www.springer.com/978-3-319-62541-6

Representing Scientific Knowledge
The Role of Uncertainty
Chen, C.; Song, M.
2017, XXXII, 375 p. 200 illus., 165 illus. in color.,
Hardcover
ISBN: 978-3-319-62541-6