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Innovative Collaboration and Acceleration: an Integrated Framework Based on Knowledge Transfer and Triple Helix

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Abstract

Although the triple helix model has successfully explained the complex evolution of multi-agent interaction in the innovation ecosystem, further research is still needed to classify and examine the mechanism of micro-innovation systems. Different from previous work, we regard the research institution as an independent innovation unit, and on this basis, we redefine the efficiency of the innovation system from the perspective of the collaboration and spatial relationship among the innovation units. In this way, the innovation system is actually carried out based on the accumulation of knowledge in the innovation unit, on the collaborative efficiency as the driving factor, and on the conditions of economic equilibrium under local resource constraints. The microscopic description of mathematical modeling clarifies the interaction mechanism of innovation units and provides a new angle for evaluating the efficiency of innovation systems. In addition, the model can better understand the evolution direction of innovation systems under the acceleration of changes in the economic and knowledge creation paradigm, and it also provides quantitative ideas for predicting the development of future innovation systems.

Keywords Economic equilibrium · Innovation ecology · Innovative collaboration · Triple helix

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Introduction

The concept of the national innovation system was first proposed by British economist Christopher Freeman in Technical Policy and Economic Performance: Experience from Japan in 1987 and in Japan: A New National Innovation System in 1988 (Freeman, 1987). This system relates to both public and private industries—their activities and interactions determine the network of various systems for and during the launch, import, improvement, and diffusion of new technologies. Freeman used this framework to study the rise of the Japanese economy after World War II from several aspects such as corporate research and development departments, government, education, and training. According to Freeman, his model could reasonably explain the rise and fall of the national economy from the perspective of national innovation and systems. The concept of the national innovation system originated from a systematic methodology of analyzing innovation processes. Research in this domain predominantly focuses on the interconnections and interactions among elements in the innovation system (such as government, universities, and industry). Since its conception, the discussion of such related relationships has gradually become complicated (Gancarczyk, 2015; Kudrina & Omelyanenko, 2018; Lundvall et al., 1992). In practice, the sources and causes of innovation are diverse. Systematic research identifies such complexity of innovation processes—that is, the overall innovation capacity depends on how innovation institutions interact as elements of the knowledge production and use system as well as with the relationship of social structure (Montalvo & Moghayer, 2011). Early research on innovation systems emphasized the closed innovation of individual enterprises and the role of entrepreneurs. Later, these enquiries expanded to research in open innovation in order to understand the interactions among enterprises and the collaborative cooperation of the industry, university, and innovation research. Scholars abandoned simple linear analyses in favor of a more systematic and comprehensive exploration of innovation. It was evident that enterprise innovation is not an isolated behavior, but cooperative behaviors among organizations. These relationships were found to be highly interdependent, where members participated in a unified ecological framework for learning and evolution. The elements of the innovation system were diversified and more complex now. As a result, the innovation system itself began to be seen as highly mutable; it was characterized by fluctuations in its evolution. This fluctuation is best expressed as accelerations and decelerations at certain levels in certain periods (Ivanova & Leydesdorff, 2015). Currently, the triple helix conceptual framework offers a better description of this dynamic process. The triple helix combines the two innovative theories of state interventionism and laissez-faire (Etzkowitz & Leydesdorff, 2000). In national interventionism, the state decides on the allocation of resources for universities and industries, subjects of university research, and direction of industrial development. Each of these three roles is mutually supportive and restraining—a relationship that is indispensable for constructing the innovative ecology. Etzkowitz introduced this model in economics to better explain the core position of knowledge sharing between universities, governments, and enterprises in the development of a knowledge economy in an innovation system. Tripartite cooperation and promotion of knowledge sharing are considered important factors driving the development of innovation. In the process of transforming knowledge non-linearity into productivity, all participants jointly promote the rise of the innovation spiral and finally reach the goal of knowledge innovation. In the knowledge economy, the triple helix model theory is critical to explain how knowledge innovation is achieved and knowledge is shared in R&D activities. Through this theory, we can further understand the interaction relationships among different knowledge subjects in R&D activities and the different knowledge innovation subjects in multiple interaction mechanisms between different stages (Faria et al., 2019; Lee & Kim, 2016; Ranga & Etzkowitz, 2013). The triple helix structure model mainly focuses on the interactive relationships between government departments, universities, and enterprises. In actual R&D activities, there exist three public science and technology intermediary service institutions with communication, financing, and consulting functions along with cooperative and innovative knowledge sharing; these institutions are catalysts for knowledge sharing and other aspects (Leydesdorff & Meyer, 2006; Leydesdorff, 2012a). In the advanced development of the triple helix structure (e.g., four- and five-helix models and other important theoretical frameworks of innovation systems), scholars have introduced other dimensions such as media and public awareness to describe innovative ecological evolution in high-dimensional situations (Carayannis et al., 2018; Leydesdorff, 2012b). These models do not necessarily perfect and complement the triple helix system, but classify the innovation system in a broader dimension. This improves the understanding of the innovation paradigm process at different levels (Ivanova, 2014).

The present study differs from the higher-dimensional N-spiral model framework by expanding the traditional three-spiral framework. We merge the dual views of interventionism and liberalism and internally stratify the innovation units in the model framework, such that each innovation unit realizes the characteristics of the opposite unity, which we call the spatial triple helix model (STH). We also introduce a step development perspective of knowledge (Carayannis & Campbell, 2017, 2019; Carayannis et al., 2016), starting from the synergy of innovation and the driving force for development in order to describe the innovative relationship of the extended STH. By introducing the concept of innovation unit and subspace, we describe the flux model of subspace and the efficiency of the overall innovation system. We conduct further analysis of the system's innovative acceleration characteristics and other important state metrics for the special organization of the STH. Notably, these characteristics are presented in a locally optimal way, which also reflects the local economic equilibrium characteristics of the system. These features can help the formalization and operability of non-linear dynamics and reveal the hidden features in the phenomenological description.

Finally, combining the two proposed system variables, we can grasp how the four innovation units of industry (or business), university (science), national research institution, and government interact to evolve the micro-innovation ecosystem. From this perspective, the STH model is not only special because it enables us to create an effective system to measure the effect of innovation collaboration on the overall innovation performance of the system—it also offers the key to understand the local innovation mechanism of the system within a certain period. The remaining paper is organized as follows. In the "Some Issues in the Traditional Triple Helix Model" section, we describe the classic triple helix model, especially the expansion and asymmetric description of micro-innovation units. We then propose directions in which this framework can be expanded. In the "The STH System Framework" section, we propose the STH innovation system model to integrate the asymmetry of the system. The STH model can be partially described as an optimal development path problem under the constraints of economic resources. The system reaches the optimal level of the stage through local equilibrium. We further explain the characteristics and meaning of introducing metrics, decompose the system dynamically from the aspects of collaboration level and collaboration rate, and describe the final innovation path of the system coupling these two changes in space. In "The STH System Framework" and "Policy Implications" sections, we summarize and conclude the study.

Some Issues in the Traditional Triple Helix Model

Triple Helix Model

The triple helix model is further developed based on national interventionism and laissez-faire theories from confrontations among subjects; it emphasizes that innovation arises from the interaction and progress between the government, industry, and university. These three elements, as stated before, are mutually supportive, restraining, and indispensable. This interactive advance is not linear—such as a simple linear transition from basic research to applied research—but a complex spiral one. That is, the three chains must cooperate to reduce mutual restraint and achieve overall efficiency improvements through resource sharing and information exchange. Thus, with the dynamic changes of social boundaries, different institutional areas have acquired inter-penetrating characteristics of diffusion. They overlap and

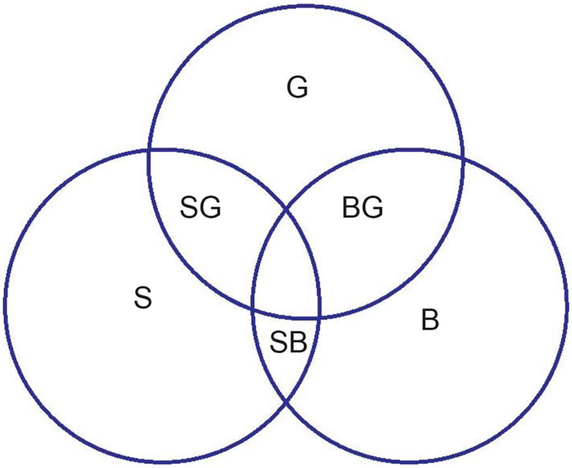


Fig. 1 Schematic diagram of the triple helix interactive system in Ivannov (Ivanova, 2014)

the functions of each participant in the intersection interchange. In addition to its basic characteristics, each institutional field has acquired other characteristics. For example, Ivannov (Ivanova, 2014) describes the triple helix as follows: during evolution, two overlapping areas SG, SB, and BG appear, as shown in Fig. 1.

The triple helix model plays an important role in understanding the micro-innovation ecology, nevertheless in many cases it also has some limitations. For instance, it does not offer a specific interaction process regarding how the three innovation units function at the micro-level. Scholars have, however, improved upon the triple helix model and measured the innovation ecosystem classification thereof (Leydesdorff & Ivanova, 2016; Miller et al., 2018). The multi-spiral model promoted based on the triple-spiral framework only considers the changes in the innovation unit, but the description of the relationship between them is not clear. In addition, as the dimensionality increases, the way to represent the relationship between innovation units with overlapping areas is too complicated, which is not conducive to measuring the energy efficiency of innovation systems or subsystems. Therefore, in addition to finding a more suitable innovation system model, it is also important to increase the quantitative method for describing the mechanism of action between innovation units.

Extension of Micro-innovation Units

As a conceptual tool, it is necessary to further distinguish the subject innovation units in order to better understand the evolution of the increasingly complex relationship between universities, companies, governments, and society in the context of public science. In fact, the main forms of knowledge generation and original innovation have also changed. From the knowledge innovation theory of model 2 to model 3, the boundaries of universities and enterprises as the main innovation function areas are becoming increasingly clear. The research unit of the institute has been gradually separated from the binary classification of universities and enterprises, forming an innovative basic unit with unique attributes (Feng et al., 2010; Ju, 2003; Teece, 1985).

Research institutes often have some advantages that universities and enterprises do not have, but they are characterized by the pure attributes of both. Between them, national scientific research institutions are more representative. Presently, research institutions, universities, and corporate R&D institutions together constitute a “troika” that promotes the development of science and technology. Below, we discuss the necessity of introducing independent innovation units represented by national scientific research institutions from different perspectives.

First, let us consider knowledge innovation and transfer. Through the interaction and circulation of knowledge, the three units of enterprises, universities, and national scientific research institutions are in different positions in the innovation value chain. They, thus, form an orderly division of labor and mutual cooperation (P´ovoa & Rapini, 2010; Rao et al., 2012). Between them, enterprises focus on technological innovation and application of knowledge, while also disseminating knowledge. Universities focus on knowledge transfer and training of high-quality talents, while carrying out knowledge innovation and knowledge transfer. They focus on free and flexible scientific exploration (Maleki et al., 2014). National scientific research institutions work in research related to the long-term social and economic development, national security, and public health of the country and strategies thereof (Smeby, 1998).

Second, from the perspective of organizational form, traditional universities still primarily conduct basic research, where strong academicity is the starting point of knowledge transfer. The organization of innovation activities in colleges and universities is relatively fragmented, the innovation units are relatively lonely, and a few influential leaders can organize larger-scale projects to form individual teams. Research institutes represented by national scientific research institutions include large-scale comprehensive national scientific research institutions and professional scientific research affiliated to the department. Some of these institutions are jointly established by central and local governments, while others are entrusted to universities or enterprises to manage (Dusdal et al., 2020; Powell & Dusdal, 2017). Enterprise R&D is also similar to scientific research institutions. It is also the subject of certain departments in the enterprise. A large number of personnel are organized to conduct research and R&D on a certain subject, and this dynamic manifests as the strong cohesion of innovation units (Sun, 2013).

Finally, let us consider the perspective of input and output factors. The input elements of traditional colleges and universities for innovation activities are often funds and elements. These elements include various physical elements such as experimental scientific instruments, human resources, and venue facilities. Output is relatively a form of native knowledge represented by papers and patents. The input elements of the innovative activities undertaken by the institute are similar to those of universities, but they often have more practical characteristics. They can be a certain form of product or they can be a technical form generated by processing the original knowledge (Griffiths, 2004; Silverberg & Verspagen, 2007). The innovation activities undertaken by enterprises are very different from input and output factors. The purpose of the enterprise is the practicality of the product, and, hence, basic R&D exists only in a few large enterprises. The demand for secondary knowledge forms and technologies is often greater than the innovation unit highlighted above (Vincent et al., 2015).

Asymmetrical Characteristics of Innovation Units

Prior triple helix research on the function and evolution of innovation units has extensively classified and described the space–time evolution characteristics of each innovation unit. The process of increasing the number of innovative system models that require classification is a way to add new sizes. Ivanova (Ivanova, 2014) proposed that a “triple helix” can be formed in a unique way, but it can constitute a higher extension in many possible ways and, thus, be classified according to its topology or symmetric structure. Afonso et al. (Afonso et al., 2012) further developed innovative concepts through a quadruple helix based on four driving factors: academic and technological infrastructure, business, government, and civil society. The five-element spiral theory emphasizes the necessary social and ecological evolution of society and economy in the twenty-first century (Carayannis et al., 2012). The latest method that attempts to improve the structure of all spiral models has been associated with this ecological spiral, conceptualized as a “life laboratory” (Baccarne et al., 2016). To develop the descriptive function of the triple helix more fully, studies have added some knowledge and innovation space in the relationship between the government field, researchers, and other innovation units. These spaces interact and merge the roles of each participant. The equality of the triple helix governance structure strengthens the discussion of strategic issues, thereby promoting the dissemination of knowledge among the constituent subjects. Although the triple helix model equalizes the status of the government, enterprises, and universities, this equalization does not mean that each innovation element contributes equally to the development of the triple helix.

In fact, the early triple helix model originated from two ideas of state interventionism and laissez-faire liberalism. State interventionism emphasizes the state as the subject of innovation units, encompasses academia and industry and directs the relationship between them. Laissez-faire liberalism believes that innovation units with strong borders dividing them and highly circumscribed relations among them. The innovation system can go further only when the parties are loosely connected and the containment is minimal. Notably, these two forms of existence are not incompatible. State interventionism actually fully embodies the particularity of the state as an innovation unit. In state interventionism, the state decides the allocation of resources for universities and industries, plans the subjects of university research, and directs industrial development. However, for laissez-faire liberalism it is a complex interactive performance performed by the government, industry, and universities. In wartime or project breakthrough period, the form of state intervention may be an effective innovation system structure, but the breadth and sustainability of its innovation will be challenged by the interaction of other innovation entities.

Although the triple helix model reflects the dual characteristics of interventionism and liberalism to a certain extent, it more often equals the status of government, enterprises and universities. The triple helix model makes no distinction between the status of the government and other innovation units, which greatly weakens the characteristics of state interventionism. It can be found that this asymmetry is hidden under the concept of triple helix planarization. The government can take actions at the national, regional or increasingly international level, so it often appears as a leader in the formation of a complex gameof innovation units. Other innovation units often appear as followers, and they adopt appropriate attitudes through their own decisions. But this does not mean that the forerunner of the system can only be the government. For example, applied innovations in the industry may induce changes in the overall performance of the system. The disturbance will gradually be transmitted to the interior of the relevant innovation unit, affecting its evolutionary mode. But at a certain moment, the degree of influence from the innovation unit on the efficiency of system innovation is different, and in most cases, the government plays this role.

The STH System Framework

Elements in the STH System

According to the discussion in the previous section, we first describe the expand the national innovation system and the way in which its internal innovation unit manifests through a conceptual diagram in Fig. 2. As discussed in the "Some Issues in the

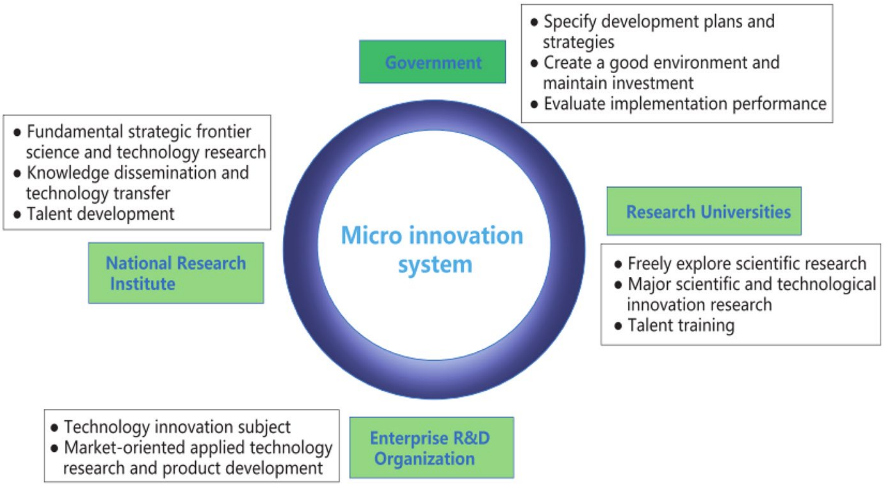


Fig. 2 Extensive micro-innovation system

Traditional Triple Helix Model" section, in the expansion of the micro-innovation system, the national scientific research institution has become an independent new innovation unit along with the government, research universities, and enterprises. The latter three are conceptually consistent with the traditional triple helix model. However, the expanded micro-innovation system can also determine the special position of the government in all innovation units. The government plays a leading role under certain circumstances, and it induces corresponding policies and evaluation methods to enable the collaborative development and efficient operation of innovative systems.

Structural Form of the STH

To undertake the previous problem, if we planarized feature description as in Fig. 1, it will fall back into the current N-spiral frame method. This way, the relationship between innovation unit derivation and innovation cannot be better reflected. We know that economic growth depends not only on the new cycle of innovation, but also on the structure of innovation that is increasingly connected to both basic and applied research (Leydesdorff et al., 2006). If universities represent the creation of intellectual capital and scientific knowledge, the industry represents the creation of economic wealth; it reflects corporate strategies. Then, public institutions represent the main battlefield for major national applications and the government becomes the mechanism of control and regulation by enacting or implementing the laws and regulations of policymakers. Policies, strategies, and actions. These different subjects mutually and reflexively react to the other??s actions as well as innovative systems develop based on these actions and mutual adjustments. When the national research institute was gradually differentiated from the innovation system, the traditional triple helix model evolved similar to the quadruple helix system because there were four actors at this time. However, the new quaternary relationship is slightly different from the quadruple helix relationship, given that national research institutions do not constitute a new dimension in the innovation ecosystem. In terms of playing a role, it is still similar to universities and industries, but only in knowledge. The organization and transfer process present a unique structure. To distinguish this new quadruple helix structure, we use the STH structure to understand it.

As shown in Fig. 3, the four vertices of the space tetrahedron ABCD represent the four innovation units here, namely, government, university, research institution, and enterprise. Then, how does this expression of innovative ecology reflect the interaction and evolution between them? Indeed, every three actors can form a local innovation ecosystem—for example, the three ecosystems of ABC, ACD, ABD, and BCD. The line segment between the other four vertices is also a binary relationship representing degradation. There are six sets of relationships here. This description method is different from the coordinate method (Ivanova & Leydesdorff, 2014) and the circular method (Carayannis & Campbell, 2017). The expression here emphasizes the interactive relationship with, rather than the role of, an individual in the innovation system. The overall efficiency of the system is completed through the interaction process between each innovation unit. If the connectivity of certain two innovation units is not favorable, then the entire knowledge transformation chain is incomplete. We define such a situation to be not connected. A more intuitive explanation is that, for an ecosystem, when the degree of mutual information between the government and the research institution is insufficient, the length of the AD side will be so small that the space tetrahedron degenerates into a two-dimensional situation. The situation evidently can take the following forms, for example, at this time, point "A" can be inside, outside, and on the boundary of triangle BCD, as shown in Fig. 4.

At this time, although the system has certain connectivity, the conduction efficiency of A—that is, the shortest path of knowledge transfer—has not been formed

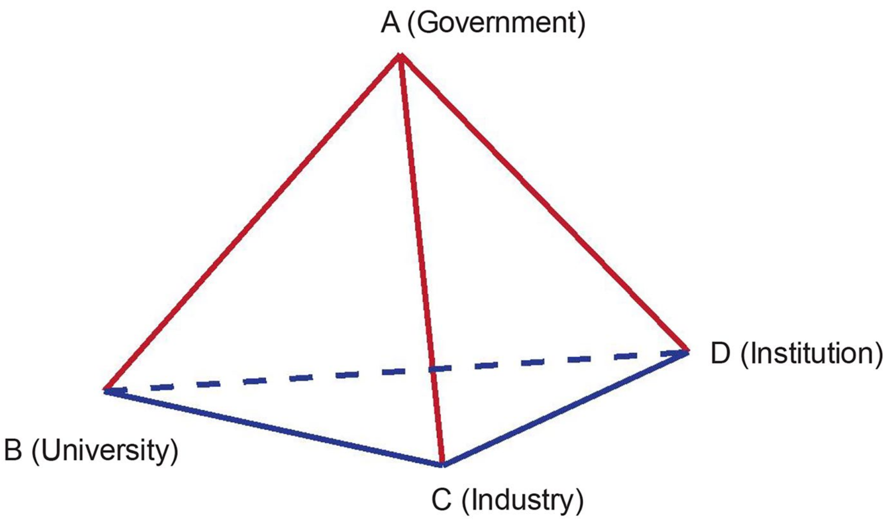


Fig. 3 Extensive micro-innovation system

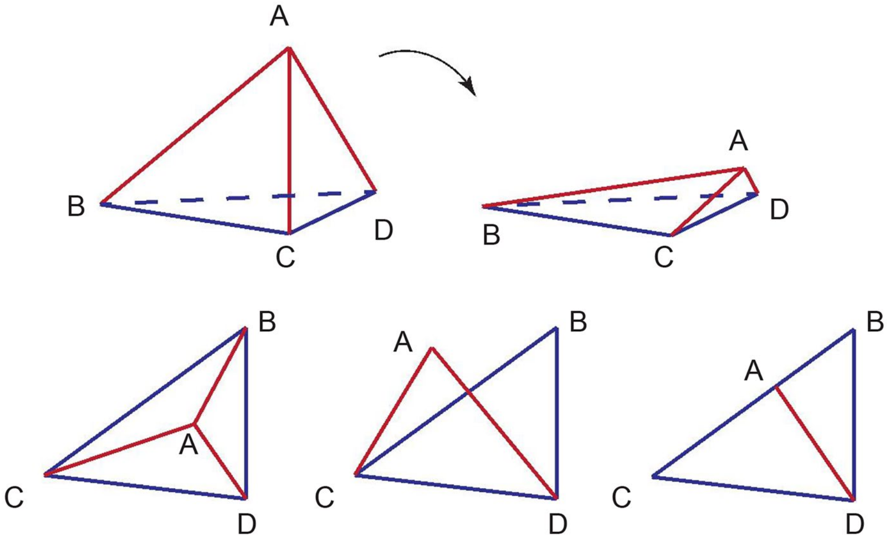


Fig. 4 Extensive micro-innovation system

(ideally, A–D). It needs to be realized through B and C, although we still do not believe that such a connection method is effective. When considering the STH structure, we do not consider this two-dimensional degradation as a result. Then, the measurable innovation evolution system is defined as follows:

$$\Xi = \left\{ \left(v_i, d_i\right) | v_i \in V, 0 < d_{ij} = \left\| v_i - d_i \right\|_{i \neq j} < \overline{d}_{ij} \right\}$$

where V is the collection of all innovation units. d is the distance between any two midpoints of V; we define it as the “innovation flux” between the subsystems or “flux” for short. The tetrahedron formed by the innovative system of the three-dimensional space defined in this way has a completely non-degenerate form. It also represents the upper bound of flux. This parameter can be determined by the current cooperation potential of the innovation unit with other innovation units or the level of knowledge absorption and transfer (Miller et al., 2016). The innovation systems we discuss below are based on the elements in the collection. We call the expression of this innovative system a spatial superstructure of the traditional triple helix model or super triple helix model.

The Conceptual Understanding of Knowledge and Innovation

Innovation Unit and Innovation Relationship

One of the characteristics of the STH model is that it highlights the synergy among innovative units, which simultaneously integrates the system characteristics of centralization and free development into the conceptual framework. Thus, what is the relationship between this relationship model that represents innovation units and the traditional triple helix model? From our perspective, it makes sense that the STH models defined based on innovative relationships and on individual innovation are interchangeable. The consequences are:

- The existence of the innovation relationship reflects a certain level of aggregation of innovation units and vice versa.
- The relationship among innovation systems abstracts the level of knowledge transfer among innovation units and avoids the discussion of meaningless isolated innovation units.
- The innovation level of the innovation unit often affects the corresponding innovation relationship, and it is more meaningful to discuss the innovation relationship with a connected structure.
- In some characterization methods, the innovation unit and the innovation relationship coexist. Innovative relationship-based analysis and interactive representation based on innovation units are also possible, but more complex representations are needed.
- This way, when discussing the integrity and innovation efficiency of the innovation system, we start with the innovation relationship. In the case of the focus type of "knowledge production" or "knowledge processing" innovation, innovation is almost automatically achieved. However, only a synergy among multiple innovation units can effectively transfer and upgrade the knowledge among innovation units to form the real kinetic energy of the system. Even if we focus on knowledge innovation based on innovation units, we must admit that the significance of knowledge innovation in isolated innovation units is not obvious. The systematic structure of knowledge proposed by Carayannis et al. (Carayannis et al., 2016) emphasizes a path of knowledge upgrading and knowledge change, particularly with the aggregation effect of innovation units and the fluidity of knowledge from R&D to S&T to innovation—this is the real process to complete this process.

To further illustrate our point, consider, for example, the concept of "National Innovation System," or that "National Innovation System" is the most prominent manifestation of the innovation relationship in the macro sense as well as the stable and sustainable formation of the innovation connection between innovation units innovative system (Nelson, 1993). The effective knowledge evolution mode here should be a three-dimensional driving method, as shown in Fig. 5.

Flux and Level of Coordination

In this section, we discuss how to understand the overall efficiency of the innovation ecosystem from the perspective of collaboration among innovation units. First, no interaction among the innovation units may result in a situation where the traffic police of the road are in charge. Although each innovation unit can develop well enough, the contribution level of each innovation unit to the innovation system is weak or there is no good innovation relationship among the innovation units. At

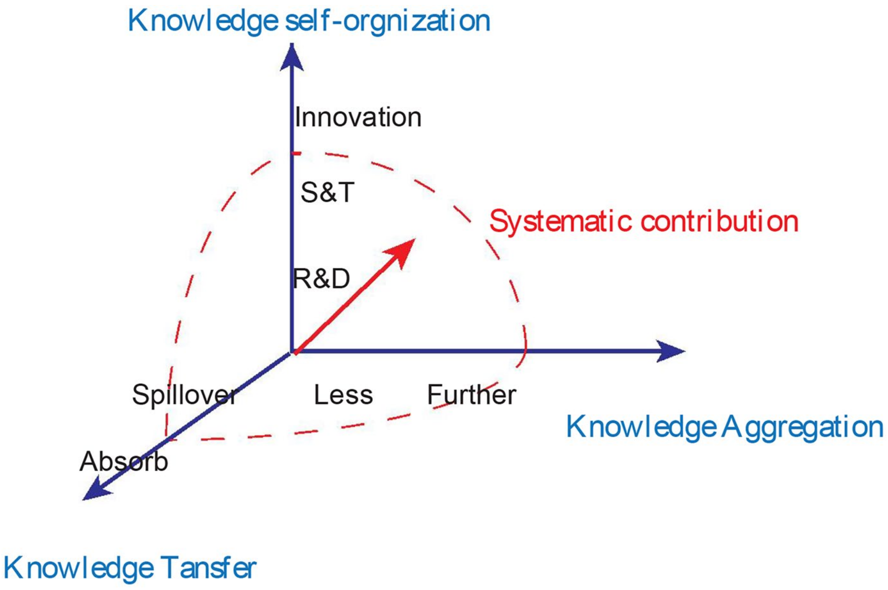


Fig. 5 System contribution level of an innovation unit driven by three-dimensional knowledge innovation

this time, the system integrity and energy flow cannot be well integrated. A natural method here is to define the volume of the STH tetrahedron as the synergy level of the innovation system. That is, for a measurable innovation system, we define the innovation efficiency of the system as the volume of the corresponding space tetrahedron as follows:

$$M(\Xi) = \iiint_{S^{\circ}} d\Lambda.$$

Among them, $\partial S = \left\{ v_i v_j \mid i \neq j,\ v_k \in V \right\}$ is the boundary formed by the connection between each innovation unit, S° is the interior of this polyhedron, and Λ is an orthogonal rectangular coordinate system in the space where it is located. The efficiency of the innovation system is defined as the corresponding two-dimensional subspace, that is, the length of six edges $M\left(\Xi_{ij}\right) = d_{ij} = \left\| v_i - v_j \right\|_{i \neq j}$. According to the discussion in the previous discussion, it is called the flux generated between subsystems i and j. The concept of flux is a measure of local collaboration of the innovation subsystem. Indeed, according to the definition of the measurable innovation system, the innovation system composed of all two-dimensional subspaces of the innovation system, we studied here is also meaningful, namely, $M(\Xi_{ij}) > 0$. At the same time, it should also be found that, when $M(\Xi_{ij}) \rightarrow 0$, $M(\Xi) \rightarrow 0$. That is, when the innovation effi-ciency of the subspace is very low, it also affects the innovation level of the entire innovation system. The measurement of the innovation relationship here shows that the capacity of the innovation system is directly proportional to the exchange flux of the link as a binary channel of the exchange and the network link. It is feedback arising from ternary or higher order interactions. The interaction among system selection environments can, thus, provide synergy (Ivanova & Leydesdorff, 2014, 2015). Below, we use examples to illustrate the rationality of such defined innovation levels. Let us consider some relatively simple innovation cases. For example, consider the current innovation system, with three two-dimensional subspaces: school–research institute, research institute–enterprise, and school–enterprise innovation relationship. Suppose that among the subsystems formed by these three subspaces, the flux level between two pairs is given (they are related to the current knowledge stock of each innovation unit, spillover level (Kamien & Zang, 2000), and absorptive capacity (Miller et al., 2016)).

Therefore, in the short term, the flux of the subsystem is stable (the exchange limit of the binary channel $\overline{d}_{ij}$). At this time, for the government, the possible flux pattern of its own innovation value is undecided. We consider the following forms:

In the above three innovation systems, BC, CD, and AD represent the three groups of innovation relationships of university–research institute, research institute–enterprise, and university–enterprise, respectively. Given the level of synergy, because of the spillover effect of the government at point A on other, the fluxes generated by the three innovation units are different, which results in three different innovation models: I, II, and III. In system I, the government's flux to the other three innovation units is relatively average. In II, the government's flux to C or D is larger than B. In III, the government's flux to B or C is much larger than D. If it is assumed that the distances between point A and plane BCD of systems I and III are the same, then, although the position of point A in space is uncertain, the overall innovation level of the two systems is the same. However, we know that the topological forms of these two systems are still very different.

Similarly, for I and II, the relative positions of points A and BCD are different, and, hence, the measurements of their respective systems are definitely not equal because the existence of point A in the space, AB, AC, and AD cannot be completely liberalized. That is, the government needs to meet certain constraints on the flux of the other three innovation units. The more meaningful approach here is to constrain the measure to a sub-manifold to obtain the optimal distribution of point A. Therefore, the government's execution efficiency is shown to be optimal at this time. Here, the government generates synergistic fluxes AB, AC, and AD, which all require a certain cost. It is conceivable that the cost is proportional to the generated flux. This view is similar to the view put forward by Ivanova et al. Therefore, we can obtain the best government coordinates by means of optimization, namely,

$$\underset{v_A}{\mathrm{Max}} \iiint\limits_{S^\circ} d\Lambda$$

$$s.t.$$

$$\sum_{k=B,C,D} \omega_{Ak} d_{Ak} \leq \eta.$$

Note that the weight ω_{Ak} is equivalent to the unit cost of generating flux in different subspaces, but the amount of flux d_{Ak} generated by the government (point A) to each innovation unit. η is the upper limit at which the government can generate flux. This upper limit $\eta < \infty$ is determined by the scale of the government and the ability to generate knowledge in the innovation system.

The above optimization model can help us better understand the maximum synergy level that the system may produce in the case of knowing the flux of some subspaces in the innovative system. It is worth explaining that the problem is solvable. In a general sense, it determines the level of flux generation. In reality, for example, the innovation system with type-III in Fig. 6 is rare. Generally, there may be such models at an early stage of the formation of the innovation model. However, as the system is gradually optimized and evolved, it evolves from cost to flux to the optimal mode. The results obtained through the optimization model here indicate the existence and uniqueness of the optimal solution. Yet, the existence of this structure in reality also depends on many conditions because the cost of forming the cooperative flux among many systems increases, and, thus, the constraint cannot be achieved.

Correspondingly, this essential obstacle is also understandable. For example, for some national research institutions, the R&D of projects involving national security tasks corresponds to the synergy and knowledge flux. At this time, knowledge is forbidden for circulation among other research units. Moreover, in some innovation systems, considering the unpredictable external characteristics, the corresponding ones are relatively large. Then, either the corresponding innovation system is a total failure or the corresponding partial subsystems cannot pass flux.

Notably, the innovation coordination level of the spatial model can be determined by the optimal value of the formula. The constraints here are common, and, hence, other model constraints are also understandable. From another perspective, the problem is equivalent to the solution of a multi-objective problem. We can construct the corresponding problem similarly. Note that we have abandoned the optimal goal of collaborative innovation here, as we seek to minimize both the collaborative innovation and the cost function. That is,

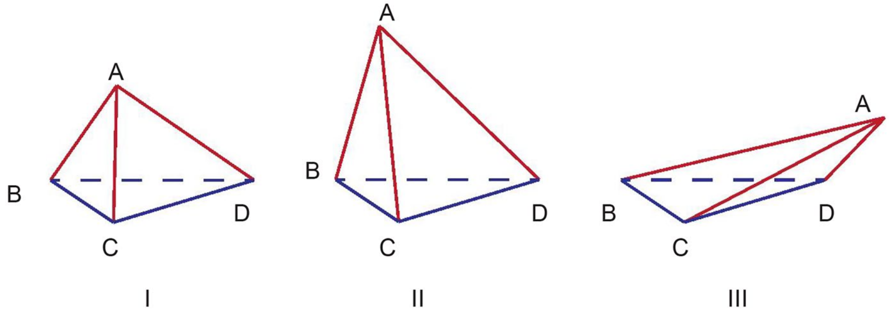


Fig. 6 Free choice of government behavior

$$\operatorname*{Max}_{v_A}\left[\iiint_{S^\circ} d\Lambda, -\sum_{k=B,C,D} \omega_{Ak} d_{Ak}\right]$$

Here, the two goals $\left[\iiint_{S^\circ} d\Lambda, -\sum_{k=B,C,D} \omega_{Ak} d_{Ak}\right]$ constitute a two-dimensional vector, and we can choose to control one variable when optimizing the decision of another variable. If the pursuit of the highest collaboration is as described in model (Elements in the STH System) and if we are to pursue the minimum cost, we can write the corresponding equation as follows:

$$\operatorname*{Min}_{v_A} \sum_{k=B,C,D} \omega_{Ak} d_{Ak}$$

$$s.t.$$

$$\iiint_{S^\circ} d\Lambda \geq \xi.$$

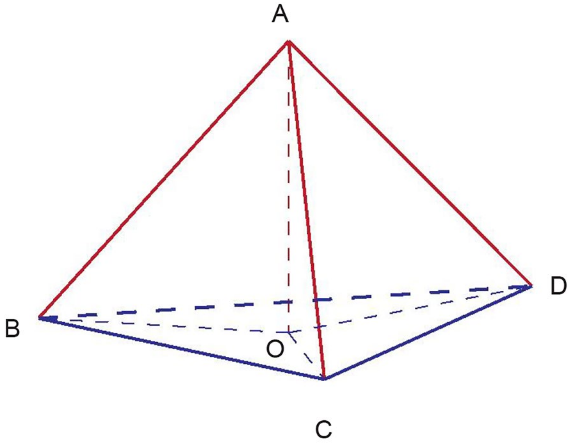
Here, ξ is our minimum requirement for the coordination level of the innovation system. Model (Structural Form of the STH) can be regarded as the dual form of model (Elements in the STH System). This relaxes the requirements for system coordination measurement and can be used as a more practical description method.

Government Induced Function

The spatial tetrahedron description of the innovation unit, in addition to introducing the important innovation element of the national research institution, is also critical because it can well represent the two characteristics of state interventionism and laissez-faire. As far as laissez-faire is concerned, it is a process of decentralization of an innovation unit. At this point, the absolute position of each innovation unit in space can be described. The question here is how to understand state interventionism within the framework of spatial tetrahedral representation. Some forms of state interventionism did exist in the early days of certain innovation systems, such as the former Soviet Union, Brazil, and France. However, some of these gradually evolved into a form of laissez-faire or the two have moderately merged. This is because the scientific and technological innovation systems of various countries are often very complex and dynamic. It is not appropriate to simply classify a certain national scientific and technological system into a certain category. As an OECD report states, although a country is close to a basic form, we cannot simply describe it as a single form (Chunli, 2013).

In the previous discussion, we discussed the system's flux and measurement forms. We now analyze the basic forms of state intervention. For innovation units, to develop a form of state intervention, there must be a dual division of the innovation

Fig. 7 The government's induced function in the STH model



system. The innovation system defined in model II is still discussed here. From a mathematical point-of-view, the projection from the government (point A) to the three-dimensional innovation subsystem BCD is the height of the tetrahedron at the bottom BCD, as shown in Fig. 7 AO. Because of the existence of cost constraints, the shape of A-BCD becomes more regular. That is, the projection O of point A on the plane BCD falls within the triangle BCD. This can be explained from the viewpoint in the previous discussion. Because each innovation unit generates flux to the other two innovation units in the innovation subsystem BCD, then, in terms of its interaction cost, there is also a path form that minimizes the energy consumption of the system. This makes BCD move toward a regular triangle-like direction of development.Furthermore, when the subsystem formed by BCD is relatively stable, the distance of AO only determines the efficiency of the system. That is,

$$\iiint_{S^{\circ}} d\Lambda = \frac{1}{3} \times \Pi_{BCD} \times d_{AO}$$

Or

$$d_{AO} = \frac{3\iiint_{S^{\circ}} d\Lambda}{\Pi_{BCD}}$$

Here, Π_{BCD} is the area of the triangle BCD. We can use the projection length of A to the subsystem BCD to characterize the intervention intensity of government A. This type of description highlights the special position of point A and regards the innovation system as a BCD development model under the guidance of A. We know that there are many ways for the government to intervene in the innovation system. The form of expression is also from top to bottom—mainly through the central government and related agencies for funding, plan design, and system and mechanism construction—in order to achieve more scientific and reasonable decision-making and coordinate various technological innovations. The unit can make better use of its related matters. In addition, the metric can also be understood from model (Structural Form of the STH).

Under the constraints of resources $\sum_{k=B,C,D} \omega_{Ak} d_{Ak} \leq \eta$, the government's ability to induce also changes within a certain range and, eventually, reaches the optimal state of the system. Foreseeably, the change in government efficiency is not monotonous. According to the dynamic evolution model of the subsystem and the efficiency of the entire innovation system, the government's induced efficiency needs to go through a series of error-and-trial processes. The final state requires reaching an ideal level $d_{AO} \to \tilde{d}_{AO} > 0$. When the government's induction efficiency is higher than this level—that is, $d_{AO} > \tilde{d}_{AO}$—the efficiency of the subsystem is not optimal. This means the government's induction is too strong at this time, and the subsystem is in an over-excited state. For example, the excessive support funds invested by the government in the innovation system have affected the vitality of the innovation system itself, and each innovation unit has created innovation inertia.

Likewise, if $d_{AO} < \tilde{d}_{AO}$, the efficiency of the subsystem is not optimal. At this time, the induced efficiency of the government is insufficient for stimulating the potential efficiency of the subsystem. Whether it is from financial means or system design, it needs to be further strengthened.

System Spin

The points we discussed above are all viewed from the perspective of state interventionism, which is actually a top-down discussion model. The bottom-up view of the laissez-faire reaction is also another main reason for the development of the innovation system. According to Caryannis (Carayannis et al., 2016), each innovation unit has an endogenous aggregation process. In this process, along with external induction (including the role of the government), innovation and knowledge spillover effects are generated, which, in turn, change the subsystem's flux and innovative efficiency of the entire system. We, thus, consider the behavior of the system in space from the perspective of self-organization, that is, the spin feature, and use it to characterize the innovation rate of the innovation system. Prior studies also recognize the problem of the innovation rate (Ivanova & Leydesdorff, 2015; Kulikowski, 2003; Roesler & Broekel, 2017). At any moment, the system has a spatial rotation state. For the sake of clarity, we take Fig. 8 as an example, assuming that AO is a fixed rotation axis in space. Then, the entire system can have two spin states: one is to increase the system rotational kinetic energy the other is to reduce. Without loss of generality, the incremental direction is clockwise and the resistance direction is counterclockwise.

We can interpret the following from the perspective of system dynamics. If we define the innovation rate of the system as ω at time t, then the system is rotating at a constant speed without endogenous and exogenous increments, which is type-II in Fig. 8. Representing the degree of knowledge accumulation as m within each subsystem, the increment seen from the physical structure Δm will produce a moment at point O, thus allowing the system to produce an acceleration effect.

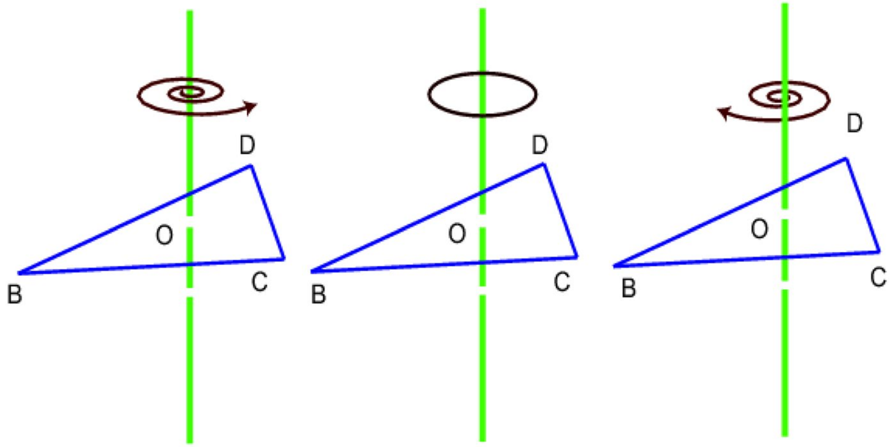


Fig. 8 The STH system spin

Notably, when the flux of the subsystem does not change, the generated torque from Δm only accelerates the system. At this time, the overall innovation level of the system does not change in Δt, but the overall innovation speed is accelerated. At the moment t + Δt, the increase in knowledge of the system Δm produces a new increase in flux Δd. This, in turn, leads to the final increase in the overall efficiency of the innovation system $\Delta \iiint_{S^\circ} d\Lambda$.

Evidently, when both Δm and Δd are increased, for an innovative unit, the "rotational inertia" of the axis AO increases. Then, the rotational speed of the innovative system becomes smaller without being subjected to external forces of the system. This explains that the completely free laissez-faire model is not the most effective, because, when the mass increment and flux increment of the innovation unit are relatively large, the system stops the acceleration process. Although there is no external intervention, for each innovation unit, knowledge generation always has a positive effect. The generation of knowledge does not always form a flux between subsystems, thereby improving the overall innovation efficiency. Yet, innovation efficiency is a non-decreasing function of knowledge accumulation. In addition to the knowledge increment of the innovation unit itself, there exist some uncertain factors, such as the system's own organization, efficiency, and other issues that will affect the quality increment of the innovation unit; we do not discuss these here. Thus, the system needs to maintain high-speed innovation momentum while maintaining the growth of innovation efficiency; it requires the form of state intervention (or other forms of external force). Judging from the form of state intervention, there are two functions—one is to provide kinetic energy for the gradually large system rotation and another is to overcome the negative resistance generated when the system rotates (these resistances are denoted as Δf). We still examine it from the perspective of system optimization, and such an intervention form needs to meet the following conditions to be optimal:

$$Max[\omega]$$

$$s.t.$$

$$\int_{t}^{t+\Delta t} \sum_{k=B,C,D} \left(M_k - f_k\right) dt = \sum_{k=B,C,D} J_k \omega,$$

$$G\left(M_k\right) \leq \Gamma.$$

Note that, here, we only discuss the dynamic situation in the moment Δt, and M_k is the moment generated by point A on BCD. J_k represents the moment of inertia of the subsystem, which is a function of system knowledge. G(·) is a constraint about the moment and Γ is a given bound. The specific form can be the investment of funds, influence of policies, improvement of systems, and other forms of government controllable resources. In addition, it indicates the corresponding upper limit of resource constraints. Similar to the definition of flux in the system in the previous discussion, we can write the dual form of model (The Conceptual Understanding of Knowledge and Innovation), which is a model that minimizes the cost of resource use:

$$\underset{k}{Min}\left[G\left(M_k\right)\right]$$

$$s.t.$$

$$\int_{t}^{t+\Delta t} \sum_{k=B,C,D} \left(M_k - f_k\right) dt = \sum_{k=B,C,D} J_k \omega,$$

$$\omega \geq \eta.$$

Here η is the lower bound of the spin allowed by the system.

In general, the curl and rotation metrics of the system we are considering here are intended to characterize the power level of the system. This is not a dimension of the system's flux efficiency. We believe that the development of system innovation—the results of the interaction between political, economic, and technological factors—evolve in two dominant forms, top-down and bottom-up, and then spread in the space of innovation adopters. In the next section, we show how the two main forms of innovative systems combined with internal symmetry can lead to non-linear and self-organizing STH systems.

Evolutionary Dynamic Mechanism

Based on the previous discussion, the function of the STH system is fundamentally different from that of the traditional triple helix system. In the traditional description process among innovative units, the two-dimensional description of the subsystem cannot reflect more dynamic information. The interaction in co-evolution may then lead to a relatively stable trajectory. The traditional triple helix dynamic analysis as such inadequately describes the source of the system's endogenous mechanism. It also cannot show how the system's endogenous variables affect each other and, thus, transfer to the existing change trajectory.

In the process of describing the STH, we accept that, in the process of self-organization, the system always selects the optimal organization form in the time neighborhood. However, this backward development model does not mean that the evolution trajectory of the system is also optimal. On a sufficiently small time scale, the spatial properties and requirements of the system can be achieved. That is, we have not adequately divided the time scale here, but approximated it in the form of a quantum. Evidently, the pattern of change between the two time scales is arbitrary. This also explains why innovation systems are always updated and evolved in a spiral rather than a monotonous mode.

However, what is the mechanism of this self-organization? Consider the metrics we currently introduce, including flux, induction, and spin and cost. Given a rotation axis, we can also describe the evolutionary kinetic energy of the system. When new knowledge is generated within an innovation unit, as internal accumulation continues to lead to the conduction effect among the subsystems—that is, the flux changes—the flux changes continue to evolve under the constraints of resources, the maximum efficiency of innovation. At the same time, according to the above discussion, the accumulation of another effect causes the system's rotational inertia to change. This, in turn, affects the speed of system evolution. Under the joint effect of these two description methods, the innovation system has completed a round of evolution.

What needs to be explained here is the unit's flux cost parameter. According to the knowledge spillover and learning-by-doing effects, the flux cost coefficient ωij is continuously decreasing, that is, $\omega ij \rightarrow \omega ij > 0$. This also causes the system flux to gradually increase. Since the flux between the subsystems is bounded, the upper bound of the flux is the maximum flux value that can be generated by the aggregation level of each innovation unit. We record this as đij. When there exists a time series of evolution of the innovation system Ξn, $\lim dij \rightarrow dij$ and $\Xi n \rightarrow \Xi$ converges to a stable innovation system. Then, the $\omega ij \rightarrow \omega\ ij$ efficiency of the innovation system is the largest. Because there are three system variables in this process, in the time dimension, the innovation system Ξn forms an innovation system column. In the spatial dimension, the innovation system column continuously produces spins in different periods with different innovation units. Participate in the dominant form. As each spin is generated, its flux and flux value also change. Figure 9 illustrates this process.

We can also understand the system evolution from the perspective of the subspace and consider BCD as an example. When the market plays a major role in

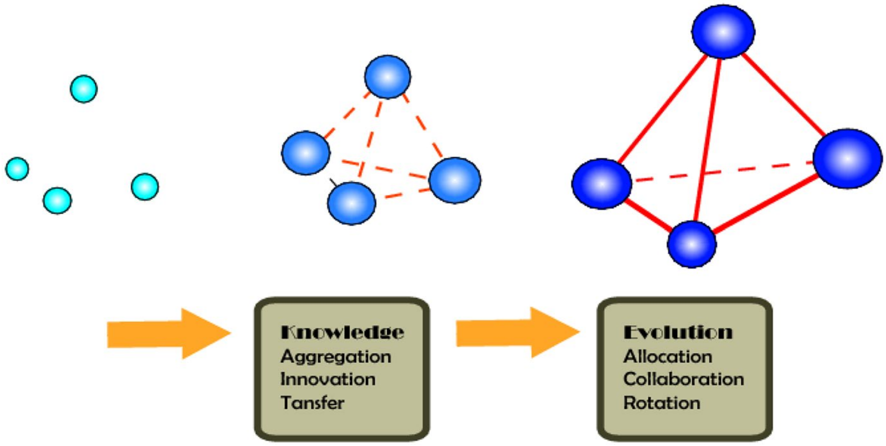


Fig. 9 The STH system spin

the development of the technical paradigm, the contribution of enterprise B will be greater than the contribution of the academic community C. When the situation changes and technical knowledge begins to play a major role in shaping the technical trajectory, the relative contributions of participants B and C will also change. Thus, government and social resources need to be redistributed between the subsystems of universities, research institutes, and enterprises. As a result, the ecological units dominated by enterprises indicate large fluxes and provide the main driving force for system spin. This process will also affect other participants one after another. When the angular momentum generated by the enterprise-based flux is dissipated by external forces, other innovation units will dominate the new round of innovation, and, consequently, a new round of evolution is conducted. During the transition of these roles, the actors are required to redistribute functions, that is, the process of redistribution of resources and flux. As the subsystem continues to lead the role rotation, the changes will gradually spread along the chain of innovation participants in the form of flux and moment of inertia. This process can be regarded as the global and local conversion of the STH system.

Discussion and Conclusion

In this study, we proposed the dimensions of the transmission triple helix structure and presented a semi-quantitative mathematical description of the dynamic mechanism and evolution of the new STH form. This new analysis framework helps us deeply understand the triple helix model—directly from the innovation relationship as the main entry point, examining the flux of the system subspace, innovation efficiency of the system, and development kinetic energy of the system. As part of the STH model, we integrate the system's innovation model from two perspectives: collaborative innovation level and innovation kinetic energy. The views based on state interventionism and laissez-faire liberalism are also well reflected in the framework. This framework combines the latest triple helix and multi-helix development research and integrates knowledge evolution and other innovative processes. Thus, we greatly improve the framework's interpretability and predictability. As the corresponding measurement mode, although we have not presented examples of further applications, these measurement modes can soundly perform theoretical and practical processes.

We draw the following conclusions based on our study:

- We expanded the structure of previous innovative units. Research institutions, especially national-level innovation institutions, play an increasingly important role in the innovation system. Their boundaries with traditional universities and enterprises are also becoming clearer. A better definition of the research institution and individual description in the innovation system can improve the understanding of the development process and collaborative mode of the innovation ecology.
- We explained the motive force generated by the innovation system. The motive power of the system comes from knowledge and the development power comes from the flux process induced by the government. The description of the model in our framework partly employs the knowledge transfer concept. From a functional perspective, knowledge aggregation may be transferred from R&D to science and technology, and then innovation. Geographically, aggregation may be directed from sub-local (local) to national and transnational. The latter constitutes the basis of flux (Kaiser & Prange, 2004).
- Through the flux description of the innovation subsystem, we reveal the overall innovative characteristics of the system. The overall innovative characteristics of the system show that under, an efficient operating innovation system, the flux among subsystems needs to meet a minimum requirement. We further explain the significance of the lower limit of the flux model from the perspective of system optimization and also prove that the overall innovation process of the system is realized because of the redistribution of innovation flux among systems under resource constraints.
- We introduce the spin state of the system to characterize the kinetic energy form of the innovative system, which can characterize the potential acceleration and trend of the system. The spin process and speed of the system are determined by the rotational inertia of each subsystem. In addition to the evolution of its own knowledge accumulation process, the intervention of government induction and resistance creates the final system dynamic torque process. In this sense, the spin form and development power of an innovation system are different from the dimensions of flux, that is, they can be used as an independent measure of innovation in a judgment system.
- The dual evolution mode of the integrated STH system can predict its future evolution mode. The STH model can be regarded as an endogenous rigid body change process system in space. Because there are many reasons for systemic resistance, the institutional communication among participants does not act as a

mechanism for generating new external choices, and the STH, therefore, contains non-innovative features of the social system.

- The spatial model expression and mathematical formulas of the STH enable us to specify a more detailed and clear understanding of the processes that occur in the STH. This also allows us to further understand the nature of the process and improve our ability to make predictions. The optimal selection method corresponding to the model can be used as the basis for quantitative evaluation of economic processes. This can also generate a broad follow-up area.

Policy Implications

The composition of an innovation system often has several main drivers, and the communication relationship among the drivers constitutes the cornerstone of its evolution. For an innovation system, although the knowledge stock of a single unit of innovation unit can be continuously iterated and evolved through the knowledge dimension, its contribution to the entire system is not necessarily great. The government should consider establishing a good communication mechanism to maintain the flux level of each sub-innovation system as an innovation unit, particularly in a resource-constrained society. The government has to consider how to allocate resources to achieve optimal operating efficiency in terms of system development power and system coordination level. The evolution of a self-organizing innovation system is not unpredictable. Knowledge is the driving force of an innovative system is still the first investment factor that every innovation unit should have. Inducing and accelerating the accumulation process of knowledge can lower the system's flux transmission cost and tilt resources more in the spin process in the form of kinetic energy. At each stage, each innovation unit will play a different role. For this, the government needs to readjust its policy orientation in real time based on the macro-response of the innovation system in order to maximize the flux value and rotational torque generated by the innovation subject within a certain period of time. Innovation policies under this system of accelerated economic and knowledge creation paradigm changes should focus more on manufacturing technology and collaboration models as well as on developing new forms of human interaction that can facilitate institutional adjustment.

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