

Evolutionary Game Theory Study on Knowledge Sharing in Collaborative Information Seeking and Retrieval: Postprint

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Abstract

[Purpose/Significance] Collaborative information seeking and retrieval is essentially a knowledge sharing process, and characterizing its dynamic evolution constitutes a core research problem. [Method/Process] Using knowledge stock, knowledge structure, and knowledge quality as variables, we construct a potential discriminant function E_{pk} for knowledge sharing in collaborative information seeking and retrieval, and employ $E_{pk}=50$ as the threshold for distinguishing high and low potential to partition the collaborative group into two subgroups. We investigate the influencing factors of collaborative information seeking and retrieval from three aspects: individual factors of participants, mutual influence among participants, and environmental effects. Based on this foundation, we apply game theory principles to construct an evolutionary game model for knowledge sharing in collaborative information seeking and retrieval. Simulation programs are developed using Matlab 2014, and multiple iterative simulations of the evolutionary game model are conducted based on given initial parameter values. [Results/Conclusion] The results demonstrate that: group participation strategies stabilize after multiple game iterations; participants' sharing/learning capabilities and inter-participant relationships exert positive influences on knowledge sharing, while cost factors have a negative impact; the evolutionary game model converges at (1,1), indicating that high-potential participants adopt knowledge sharing strategies while low-potential participants adopt knowledge learning strategies; through continuous knowledge sharing and learning in the collaborative process, the knowledge structures of all participating parties improve to varying degrees, with particularly significant improvements for knowledge providers.

Full Text

Preamble

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Research on Evolutionary Game of Knowledge Sharing in Collaborative Information Seeking and Retrieval

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Abstract

[Purpose/Significance] Collaborative information seeking and retrieval is essentially a knowledge sharing process, and characterizing its dynamic evolution represents a core research issue. **[Method/Process]** This study constructs a potential discriminant function E_{pk} for knowledge sharing in collaborative information seeking and retrieval using knowledge stock, knowledge structure, and knowledge quality as variables. Using $E_{pk} = 50$ as the threshold to divide high and low potential, the collaborative group is partitioned into two subgroups. Influencing factors of collaborative information seeking and retrieval are examined from three aspects: participants' own factors, mutual influences among participants, and environmental effects. Based on these factors, an evolutionary game model for knowledge sharing in collaborative information seeking and retrieval is constructed using game theory principles. Simulation programs were written using MATLAB R2014, and iterative simulations of the evolutionary game model were performed based on given initial parameter values. **[Result/Conclusion]** Results show that group participation strategies stabilize after repeated games; participants' sharing/learning abilities and participant relationships positively influence knowledge sharing, while cost factors have a negative impact; the evolutionary game model converges to (1,1), meaning high-potential participants adopt knowledge sharing strategies while low-potential participants adopt knowledge learning strategies; through continuous knowledge sharing and learning in the collaborative process, participants' knowledge structures improve to varying degrees, with particularly significant improvement for knowledge providers.

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1. Problem Statement

Collaborative information seeking and retrieval (CIS&R) refers to information exchange activities where users share search processes and results with others based on common interests or task completion [1], essentially constituting a knowledge sharing process [2]. However, most knowledge sharing research

merely mentions it as a factor when discussing behavioral characteristics, influencing factors, and models of collaborative information seeking and retrieval, lacking detailed description of the dynamic process. Studies show that extensive information exchange phenomena exist in CIS&R processes, with continuous exchange to reach consensus [3], and information exchange is the core element of game processes. Through information exchange, game participants continuously adjust strategies to achieve stable equilibrium. From an exchange and sharing perspective, competitive and cooperative relationships inevitably exist in user information exchange processes. Since the birth of game theory, most research has gradually used it to describe such competitive and cooperative relationships. While game theory is frequently applied in economic management research, relevant studies in the CIS&R field remain scarce. The knowledge sharing in CIS&R can introduce game theory and methods [4].

Numerous studies indicate that knowledge sharing efficiency and effectiveness are profoundly influenced by participants' knowledge structures [5-9]. How then do participants' knowledge structures affect the collaborative process in CIS&R? What are the underlying mechanisms? How do differences in knowledge structures among participants influence group members' knowledge transfer and selection behaviors? What are the evolutionary mechanisms based on such selective behaviors? This paper employs game theory thinking and simulation methods to explore these questions.

2. Knowledge Sharing in Collaborative Information Seeking and Retrieval

Collaborative information seeking and retrieval, as a possible scenario in information seeking and retrieval processes, represents a complex knowledge sharing form utilizing social intelligence [10], typically including sharing subjects, sharing objects, sharing behaviors, and sharing contexts [2]. Since the 1990s, scholars have conducted a series of fruitful studies on this form. Research shows that CIS&R is based on necessary information exchange and knowledge sharing among members within certain contexts. M. Twidale et al. noted that efficient group retrieval requires extensive communication, typically manifested as information sharing and exchange [11]. M. Hertzum found that although not all information and knowledge need to be shared in collaborative information seeking, collaboration without shared background is essentially impossible to succeed, with information sharing's main function being to guide group members to receive and understand obtained information [12].

Research reveals complex and varied knowledge sharing forms in CIS&R, closely related to sharing contexts. S. Talja identified four types of information sharing when examining academic teams' collaborative information seeking and use: strategy sharing, paradigm sharing, directive sharing, and social (interpersonal) sharing [13]. P. Hansen et al. discovered two sharing types: person-related task division, search strategies, expertise, personal ideas and experience sharing; and document-related context relationships, information need expression, informa-

tion seeking and retrieval strategies, participation and judgment, and historical information sharing [14].

Knowledge sharing can not only improve collaborative search and retrieval efficiency but also possesses knowledge creation functions. C. Foley et al., through synchronous collaborative information retrieval where two users used simple incremental relevance feedback, found that knowledge sharing improved users' retrieval effectiveness [15]. P. R. Spence found in studying collaborative information behavior that group members first jointly determine information needs, collect and share information, then use this information to jointly create new knowledge [16].

However, scholars also found that information sharing does not always exist in CIS&R processes; non-sharing phenomena also occur [12-13, 17]. Search traces (such as selected retrieval systems, used search terms, and queries) are relatively easy to share and learn, while users' search thinking and social relationships are not easily shared, and sometimes users are unwilling to share.

Collaborative information seeking and retrieval is an embedded sharing process among users, combining explicit and implicit sharing based on contextual cognition. Current research has preliminarily revealed the forms, characteristics, types, functions, and components of knowledge sharing in this process, but few studies have examined the evolution trends and characteristics of knowledge sharing under numerous influencing factors. These influencing factors can be summarized into three aspects: user factors (such as user knowledge structure, information literacy, and emotional characteristics), inter-user relationships (such as trust and connection strength), and external environmental conditions (such as availability and convenience of sharing tools and environmental tools). Since environmental impact on each collaborative participant tends to be consistent in specific information seeking and retrieval contexts, this study focuses on participant factors and inter-participant influencing factors to explore the evolutionary mechanisms of knowledge sharing in CIS&R.

3. Evolutionary Game Model for Knowledge Sharing in Collaborative Information Seeking and Retrieval

3.1 Knowledge Potential Principle of Knowledge Sharing

Evolutionary game theory originated from genetic ecologists' game analysis of animal and plant competition and cooperation behaviors, with models mainly describing how game participants adjust behaviors during repeated dynamic games to readapt. Collaborative information seeking and retrieval is a social group cognitive behavior in the dynamic process of participant interaction, where different users jointly complete information seeking and retrieval processes cooperatively, using information as a carrier for knowledge sharing and influencing each other's knowledge structures through this process [2]. Due to differences in domain knowledge richness and information literacy levels, collaborative users

always exhibit differences in knowledge stock size, knowledge quality level, and knowledge structure quality. From a physics perspective, greater knowledge stock, higher knowledge quality, and superior knowledge structure occupy more favorable knowledge potential in knowledge sharing, meaning greater potential possibility for sharing knowledge. In CIS&R contexts, common tasks or interests provide realistic platforms and transfer channels for inter-group knowledge sharing. High-potential participants share their knowledge and experience with low-potential participants, who continuously learn this knowledge according to their own needs (collaborative tasks or interests) and status, thereby improving and enriching their knowledge structures to lay foundations for group consensus formation. This is a dynamic adjustment process.

The knowledge sharing process in CIS&R is extremely complex, involving continuous mutual probing and adaptation among group users. When knowledge sharing providers decide what knowledge, experience, and skills to share, they must evaluate contributions to goal achievement and their own gains and losses, as well as assess knowledge recipients' knowledge status and willingness to accept. When knowledge sharing recipients consider whether to learn, they must evaluate the significance of knowledge learning for problem solving and their role in the collaborative process, while also assessing learning costs and benefits based on their own conditions. Regardless of subjective factors in the sharing process, objective judgment conditions inevitably exist. Observation reveals that the decisive objective factor determining sharing status (provider or recipient) and sharing efficiency is the knowledge potential possessed by the subject.

To describe knowledge potential levels of various subjects in CIS&R, we define a potential energy of knowledge function E_{pk} [18] based on physics concepts and existing research:

$$E_{pk} = m \cdot g \cdot h$$

where E_{pk} is knowledge potential energy, m is knowledge quality, g is knowledge structure, and h is knowledge stock. Here, knowledge quality, knowledge structure, and knowledge stock can be all knowledge objects of the subject or knowledge objects related to current problem solving. Knowledge stock is the subject's total knowledge quantity—the sum of knowledge at measurement time. Knowledge structure is the structural system formed by all knowledge—the relationships among knowledge elements. Knowledge quality is the grade level of the subject's knowledge structure, reflecting matching degree with specific domain problems. In certain CIS&R contexts and at specific sharing moments, participants' knowledge stock and knowledge quality are fixed, thus determining the relative position of participants' sharing capabilities is their knowledge structure difference. Therefore, the following discussion of knowledge sharing game evolution models will use knowledge structure as the main quantitative indicator.

Knowledge potential energy characterizes collaborative subjects' potential

knowledge sharing capability—a potential calculation representing the relative positional relationship of participants’ work capabilities in the system. The formula reveals that the three variables characterizing the knowledge potential function are not easily obtained through objective measurement, making knowledge potential energy merely a theoretical discriminant function.

3.2 Basic Assumptions of the Knowledge Sharing Evolutionary Game Model

In collaborative information seeking and retrieval, some participants always have higher knowledge stock, knowledge structure, and knowledge quality, thus occupying more favorable knowledge potential in collaboration. High-potential participants may become knowledge providers in collaboration, sharing their knowledge and skills within the group to improve low-potential participants’ knowledge structures. However, this process involves not simple provision and absorption but complex game mechanisms.

To grasp the knowledge sharing game process in CIS&R, this study divides collaborative participants into two groups (high-potential group, low-potential group) using a certain threshold to simplify the research process, and establishes several basic assumptions according to game theory requirements.

- (1) The knowledge potential function value range of collaborative groups is set as $0 < E_{pk} < 100$, using $E_{pk} = 50$ as the high/low potential division threshold. Participants with $E_{pk} > 50$ are classified into the high-potential group (denoted as A), and those with $E_{pk} < 50$ into the low-potential group (denoted as B). If E_{pk} calculation values exceed 100, they can be normalized to fall within the set range.
- (2) The strategy sets for high-potential and low-potential groups are (share, not share) and (learn, not learn), respectively. The high-potential group possesses relatively rich knowledge in various aspects of the collaborative group, so their strategy set is whether to share their knowledge and experience. Conversely, the low-potential group has relatively scarce knowledge, and their strategy is whether to learn to improve knowledge potential. High and low potential participants continuously improve the group’s overall knowledge potential through knowledge sharing and learning, thereby providing better knowledge foundations for problem solving.
- (3) Group bounded rationality. On one hand, participants’ knowledge potential differences and different roles in the collaborative process lead to information asymmetry. On the other hand, participants’ strategy choices are constrained by both objective and subjective factors, making participants not fully rational when selecting strategies.

3.3 Payoff Matrix of Knowledge Sharing Game Participants

As a game process, knowledge sharing in CIS&R involves information benefits for high-potential participant A's sharing participation and low-potential participant B's learning participation. According to existing research, knowledge sharing game information benefits consist of three components [19]: direct information benefits, collaborative information benefits, and knowledge sharing costs. Corresponding influencing factors can be divided into three aspects [20]: participants' own factors (including knowledge structure and self-efficacy), inter-participant influence factors (including information communication ability, strong/weak ties among participants), and participant-environment interaction factors (including task context, historical information, technical level). Specific indicators and variables are shown in .

To simplify the model, we define the following variables: knowledge structure of participant A (K_a), knowledge structure of participant B (K_b), direct information benefit coefficient (Q_a, Q_b), collaborative information benefit coefficient (N_{ab}), sharing ability (C_{ia}), learning ability (C_{jb}), sharing cost coefficient (r), and learning cost coefficient (n). The information benefits for participants A and B are shown in .

The payoff matrix for high and low knowledge potential participants is shown in .

In the knowledge sharing process of CIS&R, due to selective sharing and selective learning, let p be the probability that high-potential participant A shares experience, so the probability of not sharing is $1-p$. Let q be the probability that low-potential participant B chooses to learn, so the probability of choosing not to learn is $1-q$. The probability distributions for participants A and B are shown in .

3.4 Equilibrium Convergence of Knowledge Sharing Game Evolution

Based on the above payoff matrix and participation probabilities, the expected information benefit for high-potential participant A choosing to share is:

$$U_a = q(K_{bQ}a + N_{ab}C_{ia}K_a - rK_a) + (1-q)(-rK_a) = qK_{bQ}a + qN_{ab}C_{ia}K_a - rK_a$$

The expected information benefit for choosing not to share is:

$$U'_a = q(K_{bQ}a) + (1-q) \cdot 0 = qK_{bQ}a$$

Thus, participant A's average information benefit is:

$$\bar{U}_a = pU_a + (1-p)U'_a$$

According to game theory, participant A's replicator dynamics equation for knowledge sharing is:

$$\frac{dp}{dt} = p(U_a - \bar{U}_a) = p(1-p)(qN_{ab}C_{ia}K_a - nK_a)$$

Similarly, low-potential participant B's replicator dynamics equation is:

$$\frac{dq}{dt} = q(U_b - \bar{U}_b) = q(1-q)(pN_{ab}C_{jb}K_b - nK_b)$$

The knowledge sharing evolutionary game of two subgroups divided by knowledge potential function in CIS&R can be characterized by these two replicator dynamics equations. Setting $\frac{dp}{dt} = 0$ and $\frac{dq}{dt} = 0$ yields five equilibrium points of the knowledge sharing evolution process: $E_1(0, 0)$, $E_2(0, 1)$, $E_3(1, 0)$, $E_4(1, 1)$, and $E_5(\frac{n}{N_{ab}C_{jb}}, \frac{r}{N_{ab}C_{ia}})$.

Not all equilibrium points are stable. Their stability can be analyzed through the system's Jacobian matrix. In vector calculus and algebraic geometry, the Jacobian matrix represents first-order partial derivatives arranged in a matrix form, reflecting the optimal linear approximation of a differentiable equation at a given point. Therefore, the Jacobian matrix is analogous to the derivative of a multivariate function. By analyzing partial derivatives of p and q in participants A and B's replicator dynamics equations, we obtain Evolutionarily Stable Strategies (ESS). Analysis yields two stable equilibrium points: $E_1(0, 0)$ and $E_4(1, 1)$, representing either all high-potential participants choosing not to share and all low-potential participants choosing not to learn, or all high-potential participants choosing knowledge sharing and all low-potential participants choosing learning strategies. The latter is the desired optimal strategy and key to successful CIS&R.

Which stable equilibrium point will the knowledge sharing evolutionary game model converge to after multiple games? What trends will group knowledge structure evolution exhibit? The following Matlab simulation analysis further explores these questions.

4. Matlab Simulation Results and Analysis

4.1 Simulation Code Development and Parameter Setting

Using MATLAB R2014, we wrote simulation codes for different influencing variables of the knowledge sharing game evolution equations in CIS&R, setting different test iteration cycles as needed and continuously modifying parameters based on feedback to obtain simulation results.

Simulation calculations first require determining initial points for the evolutionary game equations. Based on the constructed knowledge sharing evolutionary game model and basic assumptions, parameters were set (see). Note that model

establishment occurs in an ideal environment with some subjective parameter settings, but tests show that parameter value variations within certain ranges do not change simulation results.

4.2 Simulation Results and Analysis

The simulation process controls other parameters within a certain range while iteratively observing the relationship between each parameter variable and participants A and B's knowledge sharing/learning probability selection. The following simulations examine evolution trends with sharing ability C_i /learning ability C_j , strong/weak ties N_{ab} , knowledge sharing cost coefficient r /knowledge learning cost coefficient n , and iteration cycles t .

[Figure 1: see original paper] shows evolution trends of participant A's sharing strategy and participant B's learning strategy probabilities with knowledge sharing ability and knowledge learning ability. The figure reveals that as high-potential participants' sharing ability and low-potential participants' learning ability continuously strengthen, knowledge sharing probability and knowledge learning probability gradually increase—meaning participants gradually increase knowledge sharing through interaction in CIS&R processes. The evolution trend also shows that participant A's knowledge sharing probability is significantly greater than participant B's knowledge learning probability, possibly because participant B selectively learns from A's knowledge sharing. In summary, both knowledge sharing ability and knowledge learning ability help improve search and retrieval efficiency and promote knowledge sharing in CIS&R processes.

[Figure 2: see original paper] shows the evolution trend of knowledge sharing probability with participant relationship strength. The figure indicates that as the connection between participants A and B strengthens, their probabilities of choosing knowledge sharing and learning gradually increase, with participant A's knowledge sharing probability increasing slightly more than participant B's knowledge learning probability—meaning the impact on participant A's knowledge sharing is more significant. The figure also shows that even with strong ties, participants' knowledge sharing/learning probabilities are not 1, indicating that high-potential participants share selectively while low-potential participants learn selectively.

[Figure 3: see original paper] shows the evolution trend of knowledge sharing probability with participant knowledge cost coefficients. The figure demonstrates that as knowledge cost burdens in search and retrieval processes gradually increase, knowledge sharing/learning probabilities show a decreasing trend, with knowledge sharing cost coefficient declining faster than knowledge learning cost coefficient. This indicates that knowledge sharing parties in CIS&R suffer greater losses. When cost coefficients exceed 0.5, evolution probability values become negative, showing that participants tend not to choose knowledge sharing and learning—that is, non-cooperation. Thus, cost coefficients represent a

bottleneck for knowledge sharing in CIS&R, requiring incentive mechanisms, retrieval training, and technical improvements to mitigate negative impacts and facilitate knowledge sharing.

[Figure 4: see original paper] shows the simulated evolution trend of knowledge sharing probability in CIS&R. The figure reveals that during knowledge sharing, group participants stabilize and reach equilibrium after multiple games, converging to (1,1)—that is, (share experience, learn). Participants A and B reach equilibrium almost simultaneously, with highly consistent changing trends during evolution, indicating that sharing and learning processes develop synergistically: whatever sharing atmosphere exists produces corresponding learning atmosphere, and whatever learning attitude exists produces corresponding sharing level. Therefore, creating harmonious group atmosphere is a common requirement for group knowledge sharing and a basic responsibility of collaboration leaders. Under a collaborative atmosphere, the evolutionary game process ultimately converges to a stable participation set (share experience, learn), where high-potential participants choose sharing and low-potential participants choose learning, thus achieving stable and harmonious collaborative relationships.

After reaching evolutionary equilibrium, knowledge sharing probability p and knowledge learning probability q approach 1 infinitely, with participant A choosing sharing strategies and participant B choosing learning strategies. How then does knowledge flow from high to low potential manifest in knowledge structure changes? According to Brookes' equation, individual knowledge structures generate new structures as new information continuously increases [21]. Therefore, we can analyze different knowledge potential participants' knowledge structure change trends in CIS&R by observing knowledge structure evolution over time. Based on previous analysis, we constructed knowledge structure increment formulas for participants A and B:

$$K_a = K_a + \Delta K_a = K_a + K_{bQ}a + N_{ab}C_{ia}K_a - rK_a$$

$$K_b = K_b + \Delta K_b = K_b + K_{aQ}b + N_{ab}C_{jb}K_b - nK_b$$

[Figure 5: see original paper] shows the evolution trend of participants A and B's knowledge structures over multiple games. The figure demonstrates that through knowledge sharing, learning, and interaction in CIS&R processes, participants' knowledge structures continuously improve. The later the collaboration stage, the greater the knowledge structure change amplitude, reflecting cumulative effects of knowledge structure improvement to some extent. High-potential participant A shows greater knowledge structure improvement than low-potential participant B, reflecting to some extent the Matthew effect in knowledge structure improvement and demonstrating that high-potential participants adopting knowledge sharing strategies is optimal.

5. Conclusion

This study constructed a potential discriminant function for knowledge sharing in collaborative information seeking and retrieval based on evolutionary game theory, using knowledge stock, knowledge structure, and knowledge quality as variables. Using $E_{pk} = 50$ as the threshold, the collaborative group was divided into two subgroups. Influencing factors were examined from three aspects: participants' own factors, mutual influences, and environmental effects. Based on these factors, an evolutionary game model for knowledge sharing in CIS&R was constructed using game theory principles. Simulation programs were written using MATLAB R2014, and iterative simulations were performed based on given initial parameters.

Simulation results show that group participation strategies stabilize after repeated games—meaning CIS&R users eventually tend to choose cooperation after multiple knowledge sharing interactions. Participants' sharing/learning abilities and relationships positively influence knowledge sharing, while cost factors negatively affect it. The evolutionary game model converges to (1,1), where high-potential participants choose knowledge sharing strategies and low-potential participants choose knowledge learning strategies. Through continuous knowledge sharing and learning in the collaborative process, all participants' knowledge structures improve to varying degrees, with particularly significant improvement for knowledge providers.

Simulation research provides a means to grasp future trends of objects. This study verifies the core Evolutionarily Stable Strategy of evolutionary game theory—the stable state of evolutionary games and the dynamic convergence process toward this stable state. Research shows that during multiple game evolution processes, users continuously adjust information behaviors and eventually strategy sets stabilize. Knowledge structure improvement is particularly significant under multiple influencing factors. However, this study requires other methods for further exploration to overcome subjective parameter setting limitations. Future research will refine influencing factors of CIS&R knowledge sharing to specifically measurable ranges, build CIS&R experimental platforms to obtain real data for verifying simulation results, and explore multi-person CIS&R knowledge sharing evolutionary game processes using more dimensions.

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Author Contributions:

Wang Han: Simulation computation and paper writing;

Han Yi: Paper conceptualization and structure, guidance and revision.

Note: Figure translations are in progress. See original paper for figures.

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