# Evolutionary Game Analysis on the diffusion of General Purpose Technologies with Government Multiple Support

**Abstract:** General purpose technologies (GPTs) are seen as engines of economic growth, which is achieved through diffusion in various application sectors. The diffusion of GPTs is the key to unleashing their potential value. However, the market and organizational failure of GPT diffusion are seen as hurdles to realize this potential. To address this issue, a single-group evolutionary game model was established to analyse the GPT diffusion process and its influencing factors and reveal the evolutionary mechanism of GPT diffusion. The main findings of the study show that the GPT diffusion is an evolutionary process influenced by many factors. GPT diffusion is negatively related to adoption and commercial development costs and positively related to the success rate of commercial development. In addition, government support is found to be positive for GPT diffusion, but a disproportionate share of government funding supports dampens the diffusion process. It is also found that government funds, knowledge and technological support are conducive to GPT diffusion. The effect of knowledge and technological support on GPT diffusion is positively regulated by the technology conversion coefficient, but the intellectual property rights system has a negative impact. The study sheds light on strategic choices for the diffusion and supply of GPTs.

**Keywords:** GPTs, R&D process of GPTs; government support; evolutionary game

## 1 Introduction

Whole eras of technical progress and growth appear to be driven by a few general purpose technologies (GPTs) (Bresnahan and Trajtenberg, 1995), of which electricity and information technology (IT) are probably the two most important GPTs thus far (Jovanovic and Rousseau, 2005). GPTs have the potential to affect the whole economy and may bring about far-reaching changes in social factors, such as working hours and family life (Helpman, 1998), which can be considered driving forces for industry development and for the economic growth of countries (Qiu and Cantwell, 2018; Korzinov and Savin, 2018). For example, it is difficult to disentangle Britain's ascendancy from the steam engine, or the USA's ascendancy from electrification and the combustion engine, the arrival of microelectronics and the economic power driven by the internet shift from the US East Coast to Silicon Valley in the West (Klinger, Mateos-Garcia and Stathoulopoulos, 2021), which shows that such technological advancements have helped the development of countries and other parts of the world. Today, against the background of the industrial revolution 4.0, those countries that develop strong AI industries will be able to take a commanding position in international competition. Therefore, governments across the world are responding with national strategies to grow their AI sectors (Goldfarb and Trefler, 2018).

The role of GPTs in technological progress and economic growth is achieved through diffusion in application sectors, diffusion is the subsequent phase, and the forwards phase is supply, which constitutes the two relatively dependent phases of the GPTs' R&D process. Bresnahan and Trajtenberg (1995) constructed the analytical framework of GPTs and their application sectors, which implies a two-stage idea. In the GPT supply phase, the main focus is on the breakthroughs of GPTs. After GPTs are supplied, subsequent commercial development is needed to realize economic and social benefits by diffusion in the application sectors, which is defined as the phase of diffusion (Zheng and Ren, 2020). Therefore, the diffusion of GPTs is recognized as the key process in realizing the economic gains of GPTs. For example, information and communication technologies (ICTs) based on cheap microchips gave birth to the video game industry, which subsequently spurred the development of graphical processing units (GPUs) now used for parallel processing of information in other sectors (Owens *et al.,* 2008).

Although the diffusion of GPTs can benefit relevant industries and overall economic performance, it is normally accompanied by various challenges at the same time. The key challenge is that GPT R&D needs to deal with the dual uncertainties of technology and the market (Terwiesch and Xu, 2008; Hooge *et al.,* 2012; Kokshagina *et al.,* 2017), which is caused by the quasi-public goods characteristics of GPTs and easily leads to supply and diffusion failures (Zheng, Yang and Wang, 2019). Therefore, governments around the world have been providing strong support to the R&D practices of GPTs to release the role of GPTs in "engines of growth". Typical examples of the development of GPTs with government support include the Advanced Technology Program (ATP) of the United States, the Very Large-Scale Integration (VLSI) of Japan, the EUREKA Plan of the European Union, the National High-tech R&D Program (863 Program) and the National Key Basic R&D Plan (973 Program) of China. The quasi-public products characteristic of GPTs make government support necessary, and government policy responses must be managed dynamically (Tassey, 2005), which need to be developed on the basis of the expected benefits and risks of current and proposed R&D portfolios. In addition, enterprises are considered the key driver of GPT diffusion and are able to explore various opportunities to apply GPTs, which help overcome the "disconnection" between the supply and diffusion of GPTs (Zheng *et al.,* 2021).

This study is triggered by the inapplicability of the existing research framework, which cannot be used to study the dynamic evolutionary mechanism and influencing factors of GPT diffusion. The literature takes GPTs as an endogenous factor of production in the mainstream economically optimal (endogenous) growth model, focuses on studying the GPT mechanism promoting endogenous economic growth using the economic equilibrium paradigm from the perspective of macroeconomic effects (Bresnahan and Trajtenberg, 1995; Helpman, 1998; Sanchez-Choliz *et al.*, 2008; Carlaw and Lipsey, 2011; Soliman, 2021), focuses on the effects of GPT diffusion on secular stagnation or unemployment (engendered by the new adaptations to GPTs), and relates GPT diffusion to the income distribution and welfare effects of policy measures. However, the existing model cannot study the dynamic evolutionary problems of GPT diffusion. To this end, based on the quasi-public goods characteristics of GPTs, the existing research framework is abandoned, and evolutionary games are used to study the GPT diffusion process and its influencing factors. The evolutionary mechanism of GPT diffusion, which is good for understanding the internal evolutionary mechanism of GPT diffusion, is revealed, helping overcome the "disconnection" in the GPT R&D process.

Our goal in this work is to analyse the evolutionary mechanism and influencing factors of GPT diffusion using an evolutionary game theoretic approach. Specifically, the following problems of GPT diffusion from the whole GPT R&D process are studied. Is it appropriate to apply an evolutionary game rather than a mainstream optimal (endogenous) growth framework to GPT diffusion? How can we build an evolutionary game model of GPT diffusion by internalising the influencing factors of GPT diffusion? How does the sharing willingness of GPTs affect the diffusion of GPTs, and what role does such willingness play? What is the effect of the technical characteristics of the GPTs supplied? How do the adoption and commercial development costs affect GPT diffusion? How does government support facilitate GPT diffusion? What are the differences in the effect of the different support modes on GPT diffusion? The above questions are all interesting academic problems that need to be addressed.

In particular, the GPT diffusion process from the perspective of the GPT R&D process is considered. Thus, this process is divided into two phases: supply enterprises share GPTs with other enterprises, and GPTs are adopted and commercialised by diffusion enterprises. Accordingly, GPT diffusion is regarded as a dynamic evolutionary process in which two homogeneous diffusion enterprises balance the expected revenues of adopting and not adopting a GPT diffusion strategy. The evolutionary game theoretic approach was applied to explore the influencing factors of the strategy choice of GPT diffusion and the causes of the market and organisational failure. Theoretically, an evolutionary game model is developed to analyse the multiple support roles played by the government in the GPT diffusion process.

The innovation points of this study consider three aspects. First, starting from the GPT R&D process, this study constructs a conceptual framework for the GPT diffusion process and analyses three kinds of influencing factors: the GPTs themselves, diffusion enterprises and government supports. Second, the mainstream economic optimal (endogenous) growth framework was changed and GPT diffusion is regarded as a dynamic evolutionary process of balancing the expected revenues of adopting and not adopting a GPT diffusion strategy for enterprises. The dynamic evolutionary mechanism and influencing factors of GPT diffusion are studied by constructing an evolutionary game model. Third, attention is paid to the role of government funding and technology/knowledge support. The results show that government support is found to be positive for GPT diffusion but a distributed share of government funding support dampens the diffusion process. In summary, this study develops a new idea involving the use of an evolutionary game framework to study GPT diffusion, fulfils the application scenarios of evolutionary games, and puts forwards policy suggestions to promote GPT diffusion, thus providing references for GPT diffusion and government support decision-making.

The rest of the paper is organised as follows. In Section 2, the literature on GPT diffusion and the role of multiple government supports is reviewed. Evolutionary game theory, which is regarded as a theoretical basic, and research framework are proposed in Section 3. In Section 4, the evolutionary game model for GPT diffusion and the evolutionary stable strategy (ESS) for the GPT diffusion game are proposed. Model analysis by numerical simulation is introduced in Section 5. The main conclusions and policy suggestions are presented in Section 6, along with discussions on the research limitations and directions for future research.

## 2 Literature review

GPTs act as an engine for technological progress and economic growth by diffusion. Most GPTs play an 'enabling technologies' role, which provide new opportunities for a wide range of innovations and investments in the economy, affecting cyclical patterns and long-term economic growth (Aghion and Howitt, 1998; Lipsey, Carlaw and Bekar, 2005). It is essential for GPTs to promote technological progress in industries with a wide range of users and to drive economic growth as a whole (Bresnahan and Trajtenberg, 1995). In the seminal literature on GPTs, Helpman and Trajtenberg (1994) developed a model of growth driven by successive improvements in GPTs.

The results of which showed that long-run dynamics take the form of recurrent cycles, where output and productivity grow slowly, or even decline, during the first phase of each cycle. It is only in the second phase where growth starts in earnest, and the steam engine, electricity, or microelectronics are taken as examples to verify the results. Bresnahan and Trajtenberg (1995) built a simple model of decentralized technological progress and analysed the relationship between innovation motivation and the economic growth of GPTs and their application sectors. The results show that GPTs give rise to increasing returns to scale and play an important role in the rate of technological progress in related industries, but a decentralized economy will find it difficult to take full advantage of the growth opportunities of GPTs. In addition, Aghion and Howitt (2000) solved the empirical limitation of the research model of Helpman (1998) by endogenizing GPTs and incorporating a social learning factor. Moreover, Carlaw and Lipsey (2006) endogenised GPTs and built a nonequilibrium growth model in knowledge research, applied knowledge research and consumer goods. The above models gave technology a basic structure and changed the traditional endogenous growth model. However, there are still some inconsistent characteristics within the historical evidence, and they all contain a single GPT and dominate the whole economy. Additionally, Carlaw and Lipsey (2011) improved these deficiencies by extending their research framework in Carlaw and Lipsey (2006) by modelling multiple, coexisting, nonidentical GPTs and the structural characteristics of technology to reveal the problem of sustained endogenous growth driven by structural and developing GPTs; they also obtained the process of nonequilibrium and nonergodic economic evolution by numerical simulation. Sanchez-Choliz *et al.* (2008) proposed a model incorporating the diffusion process of major innovations and analysed macroeconomic effects on consumption, capital and aggregate output, which was an extension of the optimal growth model proposed by Freeman, Hong and Dan (1999). Recently, Schaefer, Schiess and Wehrli (2014) presented a Schumpterian model of endogenous growth with GPTs, in which GPTs are considered endogenous and randomly dependent on the stock of available application knowledge. This approach to endogenizing the arrival of new GPTs allows for a model that is more in tune with the historical reality than the existing GPT model. Moreover, Soliman (2021) considered nine robot-intensive countries in Europe as an example based on the understanding of GPTs of Bresnahan and Trajtenberg (1995), and the results showed that industrial robots were of positive significance to the economic development of all nine countries, indicating that industrial robots can indeed be regarded as a new type of GPT. The literature shows that GPTs can be used as an engine of technological progress and economic growth. GPTs have been taken as an endogenous factor of production, and the mechanism though which GPTs promote endogenous economic growth using an economic equilibrium paradigm from the perspective of macroeconomic effects. However, scholars have not explored how GPTs diffuse among enterprises, that is, whether enterprises adopt GPTs when facing new GPTs. According to the characteristics of pervasiveness, inherent potential for technical improvements and 'innovational complementarities of GPTs' (Bresnahan and Trajtenberg, 1995), based on evolutionary game theory, whether or not enterprises should adopt GPTs as a dynamic process of learning, trial and error and imitation have been considered. In addition, the dynamic evolutionary process of GPT diffusion has been analysed and research from the microcosmic market perspective has been carried out.

The influencing factors of GPT diffusion are the focus point of this study. In their groundbreaking work in the GPTS field, Bresnahan and Trajtenberg (1995) took semiconductors (GPTs) and their application vectors (ASs), such as hearing aids, radios, television sets, computers, CT scanners, camcorders, laser printers, automobile engine control systems, and so on, as an example and built the GPT-AS analytical framework. This research showed that arms-length market transactions between GPTs and ASs might result in ‘too little, too late’ innovation. Goldfarb (2002) focused on adoption patterns in the electrification of US Manufacturing from 1880 to 1930. The key finding was that significant variation in adoption rates can be found not only between industries but also different processes within industries and firms. Galliano and Roux (2007) built an ICT diffusion model and used data drawn from 5,200 industrial firms to test the model. One striking result was that the influencing factors of network use intensity played a crucial role in urban enterprises. In low-density areas, the influencing factors of network use intensity mainly played a ranking effect. Lo and Sutthiphisal (2010) took electronic technology as an example and found that knowledge spillovers between industries had little influence on the geography of crossover inventions, as well as the speed and productivity of crossover inventors. Yu and Hai (2011, 2012) claimed that diffusion channels and models were relevant for the equipment manufacturing industry. Korzinov and Savin (2018) found that suitable conditions for knowledge diffusion and R&D aggregation were needed for the realization of expected revenue of products based on GPTs. Recently, Filippova (2020) argued that blockchain was often seen as the next revolutionary GPT and proposed a research framework based on the advancements of GPTs. The GPT’s advances in the application sector and environmental factors showed that the actual impact of blockchain will ultimately depend on the speed and direction of propagation in the whole economy. Rasskazov (2020) pointed out that AI, which was regarded as a GPT, made it possible for the state to regulate the technological adaptation process of enterprises due to the potential consequences of market monopoly caused by its distribution. Deep Learning, which is the core technology of AI systems, is regarded as the latest example of the transformation of GPTs. Klinger, Mateos-Garcia and Stathoulopoulos (2021) studied the regional drivers of deep learning competitive advantage and found that strong research clusters occur in regions that specialise in research and industrial activities related to deep learning and emphasised the importance of a supportive innovation ecosystem for GPT development. The existing researches mainly focus on the significant economic impacts of GPTs, however, how to use GPTs for innovation in downstream industries (cross-invention) and what factors might contribute to this diffusion have been little studied (Lo and Sutthiphisal, 2008). In addition, the existing researches on the diffusion of GPTs are mostly embedded in the macroeconomic growth framework. For example, Bresnahan and Trajtenberg (1995) built a GPT-AS analysis framework that tended to analyse GPTs as an economic growth engine rather than to specifically study the process and impact of adopting GPTs by ASs. Carlaw and Lipsey (2011) constructed a three-sector model including pure knowledge research, applied knowledge research and consumer goods. In their model, GPTs were endogenized and discovered from pure knowledge research and diffused to applied knowledge research departments by logistic function, but they do not deeply reveal the specific influencing factors and mechanisms of GPTs diffusion. This paper focuses on the enterprise level and reveals the dynamic evolution process of GPT adoption, subsequent commercial development and the realisation of market returns.

Government support for GPT diffusion is also an important topic of this paper. Diffusion and supply are two interdependent links in the GPT R&D process. Any problems in any of these links will affect its role as the engine of industrial upgrading and economic growth (Zheng, Yang and Wang, 2019; Zheng and Ren, 2020; Zheng *et al.,* 2021). GPTs have the characteristics of pervasiveness (Bresnahan and Trajtenberg, 1995), which can also be called a quasi-public character

(Tassey, 1992, 2005; Zheng, Yang and Wang, 2019) with basic and precompetitive technical features (Gambardella and Giarratana, 2013; Strohmaier and Rainer, 2016). As a result, GPT R&D needs to deal with the dual uncertainties of technology and the market (Terwiesch and Xu, 2008; Hooge *et al.,* 2012; Kokshagina *et al.,* 2017), which makes GPT R&D face “market failure”, “organization failure” and “government intervention failure” (Tassey, 1992, 2008; Woolthuis Lankhuizen and Gilsing, 2005; Zheng, Yang and Wang, 2019). Enterprises that represent private interests are bound to “insufficient investment” in GPTs under the market mechanism (Tassey, 2005). The government, which is on behalf of social interests, can effectively balance the “insufficient investment” of enterprises in GPTs through R&D subsidies, special plans, and science and technology policies (Tassey, 1996, 1997, 2005; Zou, Li and Wang, 2019; Zheng, Yang and Wang, 2019; Zheng and Ren, 2020; Zheng *et al.,* 2021). For example, Tassey (2005) proposed an economic model of a technology-based industry and classified technologies into three categories: Infratechnologies, GPTs, and Proprietary Technologies. The public goods nature of GPTs has led to underinvestment, and appropriate government R&D support policies need to be developed on the basis of trade-offs between the expected benefits and risks of current and proposed R&D portfolios. Zou, Li and Wang (2019) applied three-way decision theory to solve the mechanism design of government support actions, which represent subsidising, delaying decision-making and not subsidizing, under the R&D of the new energy vehicle industry GPTs in China. Zheng *et al.* (2021) pointed out that government subsidies, knowledge and policy support can help alleviate the failure of insufficient investment in GPTs, and if government support is not enough or the intervention is improper, then it is easy to produce “the failure of government intervention”. However, little attention has been given to the internal evolutionary mechanism of GPT diffusion from the perspective of the GPT R&D process.

In particular, this paper, which learns from the works of Maine and Garnsey (2006), Yu and Hai (2012), Zou, Li and Wang (2019) and Xu, Zhou and Ji (2020) for reference and the work of Zheng, Yang and Wang (2019) on a single-population evolutionary model, constructs a single-population evolutionary game model for GPT diffusion and reveals the dynamic evolutionary mechanism of GPT diffusion strategies for enterprises and the role of government in the evolution process.

## 3 Theoretical Basis and Research Framework

### *3.1 Evolutionary Game*

Evolutionary game theory is the main theoretical approach used in this paper to study GPT diffusion. The theory of evolution is the source of evolutionary game theory. Alchian (1950) suggested that the selection pressure from the "survival of the fittest" makes every actor choose the best survival mode, and the evolutionary stability strategy (ESS) derived from this is the Nash equilibrium. The 1970s was a crucial period for the formation and development of evolutionary game theory, with the representative theoretical results being the ESS proposed by Smith (1973) and Smith and Price (1974) and replicator dynamics proposed by Taylor and Jonker (1978). Then, evolutionary game theory had a clear goal; that is, using the replicator dynamics selection mechanism find the ESS of the game. Recently, evolutionary game theory has received increasing attention and been widely applied to collaborative learning in online study groups (Chiong and Jovanovic, 2012), the environmental regulation strategy of local governments (Feng, Bao and Lin, 2015), sustainable green supply chains (Mahmoudi and Rasti-Barzoki, 2017; Babu and Mohan, 2018), governments' decision-making behaviours (Gao *et al.,* 2019) and technical standard competition (Zhao and Du, 2021). For example, Mahmoudi and Rasti-Barzoki (2017) built a two-population evolutionary game model and conducted a comparative analysis of government and producer objectives in the context of trade-offs between taxes and subsidies, tariffs, profits and environmental objectives. The results showed that government policy clearly affects producers' activity, competitive markets and emissions. Additionally, Zhao and Du (2021) constructed a technology (hardware) selection model using the stochastic evolutionary game method, the results of which showed that the core mechanism that led to coexistence was the inconsistent decision-making pace between consumers and software vendors. However, the study of GPTs using evolutionary game theory is rare. An example of such a study is that of Strohmaier and Rainer (2016), who considered the effects of these innovations on the economic system at the theoretical and empirical levels; and they carried out a structural decomposition analysis of Denmark from 1966 to 2007 to track the impact of the current GPT on aggregate and sectoral labour productivity growth. There are few literature contributions on GPT diffusion, especially on the dynamic evolution of GPT diffusion based on the evolutionary game theoretic approach.

The bounded rationality of players is the basic assumption of evolutionary game theory. Aoki and Okuno-Fujiwara (1996) held that bounded rationality includes three elements: inertia, mypia and trial and errors, which means that the realisation of ESS does not occur overnight but rather is a constant adjustment and improvement process of the players gradually discovering better strategies by learning and trial and error. Because of GPT diffusion needs to deal with the dual uncertainty of technology and the market (Terwiesch and Xu, 2008; Hooge *et al.,* 2012; Kokshagina *et al.,* 2017), enterprises require trial-and-error and can take time (Klinger, Mateos-Garcia and Stathoulopoulos, 2021) when facing the exploration of new GPT opportunities. For example, US factories did not start to realise the benefts of electric power until they reorganised their layout to harness the fexibility of small electric motors decades after the introduction of electricity (David, 1990). Therefore, the GPT diffusion process can be regarded as a dynamic evolution process based on the tradeoffs of whether or not to adopt the GPT strategy. Therefore, considering the problem of GPT diffusion from the whole R&D process, we reveal the dynamic evolutionary mechanism of GPT diffusion for enterprises with multiple government support, for example, subsidies and non-subsidies.

### *3.2 Research Framework*

#### 3.2.1 GPT Diffusion

In our study, diffusion is defined as the process of GPT sharing and application along commercial development sectors. Therefore, GPT diffusion consists of two phases: one is the supply process, where the 'supply enterprise' shares GPTs with other enterprises; the other is the diffusion process, where GPTs are adopted and commercialised by the 'diffusion enterprise' (who receives the GPTs from the supply enterprise). Fig. 1 presents this GPT diffusion process. As shown in Fig. 1, starting from the left, the supply enterprise must be profitable to stimulate interest in sharing the GPTs. In turn, the diffusion enterprise must also realise market revenue from GPT diffusion. Here, the diffusion enterprise first adopts GPTs, then carries out the commercial development of GPTs to form a special technology, technique or product that can be monopolised by enterprises, and finally realises the market revenue based on GPTs.

#### 3.2.2 Influencing Variables of GPT Diffusion

Furthermore, Fig. 1 shows that GPT diffusion, as a follow-up link of GPT supply, is affected by the supply side and, thus, is also inevitably affected by the various links of the GPT diffusion process.

First, with regard to the characteristics of GPTs, they are divided into three levels: basic, precompetition and applied, and their “commonality” decreases in turn. Therefore, supply enterprises that provide GPTs with different commonalities inevitably impact the adoption behaviour of diffusion enterprises. In addition, the security, stability and reliability of the supplied GPTs also affect GPT diffusion by affecting the subsequent adoption link.

Second, with regard to the GPT diffusion decision, the cost needs to be paid by diffusion enterprises to adopt GPTs. If GPT suppliers are unwilling to share, then diffusion enterprises may suffer from high adoption cost. Even if enterprises can successfully obtain GPTs, if the difficulty or costs of commercial development are high, then the expected market revenue is difficult to realise, and thus, diffusion enterprises abandon GPTs and choose other market opportunities.

In addition, due to the uncertainty and complexity of GPTs’ commercial development, the government needs to provide financial subsidies to promote the GPT diffusion process. However, government interventions can also lead to failure and exacerbate GPT diffusion challenges (Zheng, Yang and Wang, 2019). If the government intervenes inappropriately, such as a policy failure, then the problem of GPT failure will not be alleviated and, instead, can worsen. The investigation of government support in GPT diffusion includes financial support, knowledge and technical support, such as providing subsidies, tax deductions and technical equipment.

In summary, GPT diffusion is affected by GPT characteristics and the shared willingness of supply enterprises, the adoption decision of diffusion enterprises and other links of the GPT diffusion process. Effective support from government also forms an important driving force for GPT diffusion. The influencing factors of GPT diffusion are described in detail in Section 4.

## 4. The Evolutionary Game Model of GPT Diffusion

This model assumes that GPT diffusion is a dynamic evolutionary process, as two homogeneous diffusion enterprises balance the expected revenues of adopting and not adopting a GPT diffusion strategy in the context of multiple government supports. The main notations used in this study are summarised in Table 1.

### 4.1 Basic Assumptions and Notations

**(1) GPT supply:** The model assumes that GPTs are available and known to all diffusion enterprises in the industry. There are two factors that affect GPT diffusion. The first is related to the supply enterprise (share probability of the supply enterprise), and the second is technical characteristics (commonality and quality characteristics). Assuming that the share probability of the supply enterprise is $0 \le \omega \le 1$, the larger $\omega$ is, the smaller the diffusion barriers. Parameter $0 < \rho < 1$ is used to express the technical characteristics, such as safety, stability and reliability, of GPTs, the larger $\rho$ is, the higher the efficiency of commercialisation. According to Zheng *et al.* (2020), the commonality of GPTs can be described by a commonness degree that is $e$, $e \in [0,1]$, where $e = 0$ means that GPTs are an applied technology and $e = 1$ means that they are a purely public technology. The larger $e$ is, the weaker the monopoly of enterprises' benefits.

**(2) GPT Adoption and Commercialisation:** When GPTs are supplied successfully, diffusion enterprises are faced with the decision of whether to adopt them. Under the protection of intellectual property rights, when enterprises adopt GPTs, the diffusion enterprises need to pay the GPT transfer fee, which is denoted as $\pi_z$. Let $\lambda$ ($0 \le \lambda \le 1$) denote the cost coefficient of GPT adoption; $\lambda = 0$ means that enterprise that adopts GPT does not face any cost, at this point, GPT can be considered a purely public technology product, which corresponds to $e = 1$; $0 < \lambda < 1$ indicates that GPT is difficult to apply for property rights protection or the property rights system is not sound, and the cost of GPT adoption increases with the increase of $\lambda$, which corresponds to $0 < e < 1$; $\lambda = 1$ means that the enterprise needs to pay $\pi_z$ to obtain GPT, which corresponds to $e = 0$. In addition, $\lambda$ is also affected by the diffusion barriers to obtain GPTs for enterprises. According to the above, let $\lambda = (1-\omega)(1-e)$. Furthermore, diffusion enterprises need to pay the cost $c_h > 0$ of commercial development. If both enterprises choose GPT diffusion strategy, they should, on average, bear all the relevant costs of GPT adoption, and the corresponding success rate of commercial development is $x$, $0 \le x \le 1$.

**(3) Government Multiple Supports:** Let $G$ denote the government's budget of financial subsidies for every GPT diffusion enterprise. The government subsidies both parties of GPT diffusion, the proportion of which is as follows: $y$ represents the proportion of financial subsidies, and $1-y$ represents the proportion of knowledge and technical support given to the diffusion enterprise. Due to the potential value of GPTs to economic growth, the government gives more support to GPTs with a greater degree of commonness, $e$. Therefore, diffusion enterprises are supported by the government's financial support, as $yenG$, where $n = 1, 2$ denote the number of diffusion enterprises. The government subsidies for knowledge and technology will increase the efforts of supply enterprises towards developing GPTs and improve the incremental success rate $\Delta x = \tau_{k,y}\gamma$ of GPT commercial development, where $\gamma$ denotes the success rate of commercial development based on GPTs in different situations. When both diffusion enterprises choose the GPT diffusion strategy, $\gamma = x$, and when only one enterprise chooses the diffusion strategy, $\gamma = \frac{x}{2}$. $\tau_{k,y} = A(1-y)enG$ denotes the contribution rate of government subsidies to the success rate of GPT R&D, and $A > 0$ denotes the technology conversion coefficient, which represents the degree to which government subsidies is transformed to promote the success rate of commercial development. The larger $A$ is, the more accurate and efficacious it is to improve the success rate, where $\tau_{k,y} > 0$ and $0 < \Delta x < 1 - x$. In addition, the supporting policies of the government provide guarantees for the diffusion of GPTs, for example, by amending the parameter $\lambda$ to make the GPT diffusion process run smoothly.

**(4) Expected Market Revenue:** Let $2\pi_t$ denote the total revenue of the market faced by enterprises, and if both enterprises do not adopt the GPTs, they will obtain expected revenue $\pi_t$ by investing in other market opportunities. The expected revenue of every enterprise that adopts GPT diffusion is $\theta\pi_t$; let $\theta > 1$, and denotes the additional revenue coefficient for GPT diffusion enterprises by commercial development. Furthermore, diffusion enterprises can decide whether to adopt GPTs. If they adopt GPTs, they will obtain revenue $(x+\Delta x)\theta\pi_t$, where $(x+\Delta x)$ refers to the comprehensive success rate of GPT diffusion. If only one chooses the GPT diffusion strategy, the other enterprise's revenue from not adopting GPTs will lose $(\theta-1)\pi_t$, which is equivalent to the additional net revenue from the GPT diffusion strategy.

### *4.2 Evolutionary Game Modelling and Evolutionary Equilibrium*

According to the above assumptions and analysis, if both diffusion enterprises choose the GPT diffusion strategy, then their expected revenue function is described by $\Delta_1 = (x+\Delta x)\theta\pi_t - \lambda\frac{\pi_z}{2} - (1-\rho)\frac{c_h}{2} + ye2G$; if only one diffusion enterprise chooses the GPT diffusion strategy, then its expected revenue function is $\Delta_2 = (\frac{x}{2} + \Delta x)\theta\pi_t - \lambda\pi_z - (1-\rho)c_h + yeG$, and another enterprise's revenue function with the nondiffusion strategy is $\pi_t - (\theta - 1)\pi_t$. If both enterprises choose the nondiffusion strategy, then as there are no products in the market based on GPTs, the expected revenue function for them is $\pi_t$, $\Delta_1 > \Delta_2$. Then, the payment matrix of the GPT diffusion game between two diffusion enterprises is shown in Fig. 2.

To make the following analysis meaningful, let $\Delta_2 < \pi_t$, $\Delta_1 > (2-\theta)\pi_t$, which ensure that (diffusion, diffusion) or (nondiffusion, nondiffusion) is an ESS of the GPT diffusion game, marked as subscripts C or D, respectively. Furthermore, $r$ denotes the probability of enterprises who choose the diffusion strategy of GPTs, and then the probability of the nondiffusion strategy is $1-r$, $0 \le r \le 1$. Then, the expected revenue of enterprises when choosing diffusion and nondiffusion strategies are as follows.

$$\begin{aligned} f_C = & r\left(\left(x + A(1-y)e2Gx\right)\theta\pi_t - (1-\omega)(1-e)\frac{\pi_z}{2} - (1-\rho)\frac{c_h}{2} + ye2G\right) \\ & + (1-r)\left((\frac{x}{2} + A(1-y)eG\frac{x}{2})\theta\pi_t - (1-\omega)(1-e)\pi_z - (1-\rho)c_h + yeG\right) \end{aligned} \quad (1)$$

$$f_D = r(\pi_t - (\theta - 1)\pi_t) + (1-r)\pi_t \quad (2)$$

The average revenue of the enterprise for choosing the two strategies is

$$\overline{f} = rf_C + (1-r)f_D \quad (3)$$

According to Taylor and Jonker (1978), Riechmann (2011) and Boccabella, Natalini and Pareschi (2011), the change rate of the probability of enterprises that choose the GPT diffusion strategy can be expressed by the following replicator dynamic equation:

$$\dot{r} \qquad \bar{f}) \tag{4}$$

Eq. (4) shows that if the revenue of enterprises when choosing the diffusion strategy is higher than the average revenue, then the probability of enterprises choosing the diffusion strategy will increase and decrease otherwise. Substituting Eq. (1)-(3) into Eq. (4), the replicator dynamic system of choosing the GPT diffusion strategy for enterprises is written as

$$\dot{r} \qquad )\left(\Delta_3 r + \Delta_4\right) \tag{5}$$

where $\Delta_3 = ((1+3A\left(1-y\right)eG)\frac{x}{2}+1)\theta\pi_t + \left(1-\rho\right)\frac{c_h}{2} + \frac{(1-\omega)(1-e)}{2}\pi_z + yeG - \pi_t > 0$

$$\Delta_4 = \left(1+A\left(1-y\right)eG\right)\frac{x}{2}\theta\pi_t - (1-\omega)(1-e)\pi_z - \left(1-\rho\right)c_h + yeG - \pi_t < 0$$

It is easy to obtain three equilibrium points for Eq. (5), which are 0, 1 and $-\frac{\Delta_4}{\Delta_3}$. When $\dot{r}$ , the equilibrium point is an ESS, and the stability of the three equilibrium points is described in Theorem 1. The proof of Theorem 1 is available in Appendix A.

**Theorem 1:** For Eq. (5), equilibrium points 0 and 1 are the ESS, and $r = -\frac{\Delta_4}{\Delta_3}$ is the instability saddle point.

Theorem 1 shows that the evolution of the GPT diffusion system eventually stabilises at equilibrium point 0 or 1, which depends on the initial state of the system, i.e., the relevant parameters of the envolutionary game system of GPT diffusion.

**5. Model Analysis**

In this subsection, Eq. (5) was analysed using MATLAB2020a under the market mechanism and government multiple supports and the evolutionary dynamics of GPT diffusion was revealed. In the figures below, the horizontal axis $t$ denotes the time of the system evolution and the vertical axis $r$ denotes the probability of the GPT diffusion strategy being chosen by enterprises.

### *5.1 The Evolution of GPT Diffusion under the Market Mechanism*

Considering only the role of the market mechanism, $G = 0$ and $\lambda \neq 1$ represent the government that has not established a sound intellectual property protection system for GPTs.

**(1) Impact of the relevant parameters of GPT supply on system evolution.** To reveal the impact of supply enterprises' share probability $\omega$, commonness degree $e$ and technical characteristics $\rho$ on system evolution. Based on the basic assumptions and the relationships between different parameters, let $\pi_t = 8$, $\pi_z = 3$, $\theta = 1.5$, $x = 0.6$ and $c_h = 2$, as shown in Fig. 3.

From Fig. 3, it can be seen that the critical threshold of the system that evolves to different equilibria states is $r = 73.11\%$ in the initial state. This finding shows that more than 73.11% of enterprises need to choose the diffusion strategy so that the diffusion of GPTs can proceed smoothly. When $\omega$ increases from 0.3 to 0.6, as shown in Fig. 3 (embedding graph), the critical threshold of the system evolves to a different equilibrium, which decreases to 71.23%, meaning that the probability of the system evolving to equilibrium 1 increases. This reason for this is that the increasing probability of supply enterprises sharing GPTs palys a positive role in promoting GPT diffusion.

Furthermore, as shown in Fig. 4, the evolution line $r = 73\%$ in Fig. 3 is considered the benchmark for comparative analysis. When the degree of commonality of GPTs increases from 0.3 to 0.6, the critical threshold of the system evolves to a different equilibrium, which decreases to 71.23% (similar to the effect of $\omega$). The reason for this is that with the increase in commonness degree $e$, the probability of enterprises choosing the diffusion strategy increases, which is conducive to promoting the GPT diffusion. On this basis, if $\rho$ is reduced from 0.4 to 0.2, the critical threshold increases to 74.03%. The reason for this is that the degradation of technical characteristics, such as safety, reliability and stability, lowers the efficiency of commercial development, which dampen the enthusiasm of enterprises to adopt GPT and is not conducive to GPT diffusion. In contrast, it plays an positive role in the GPT diffusion. Based on the above analysis. Summary 1 can be obtained.

**Summary 1** The stronger the share probability of supply enterprises $\omega$ is, the greater the commonness degree $e$ is and the more reliable the technical characteristics $\rho$ are, the more conducive they are to GPT diffusion.

From Summary 1, the following corollary can be drawn by considering $\lambda = (1-\omega)(1-e)$.

**Corollary 1** The lower the cost coefficient $\lambda$ of GPT adoption is, the more conducive it is to GPT diffusion.

**(2) Impact of the parameters related to commercial development on system evolution.** Let the other parameters be the same as those in Fig. 3. We still take $r = 73\%$ as the benchmark line and study the effects of cost $c_h$ of commercial development for GPTs and the success rate $x$ of commercial development on system evolution, as shown in Fig 5.

From Fig. 5, it can be seen that with the increase in $x$ from 0.5 to 0.8 and the decrease in $c_h$ from 1.6 to 2.0, the system gradually evolves to equilibrium 1 at a faster speed. The reason for this is that as the success rate $x$ of the commercial development of GPTs increases, enterprises have a positive expectation of the benefits of GPT adoption, and the decrease in commercial development cost will have the same effect, which promotes the GPT diffusion. The decrease in commercial development cost $c_h$ has a similar effect as that of success rate $x$ of commercial development of GPTs. Accordingly, Summary 2 was obtained, which is as follows.

**Summary 2** The lower the cost $c_h$ is and the higher the success rate $x$ of commercial development are, the more conducive they are to GPT diffusion.

**(3) Impact of the parameters related to expected market revenue on system evolution.** Letting other parameters be the same as those in Fig. 3, and still taking the evolution line $r = 73\%$ as the benchmark, the impact of market share $\theta$ of diffusion enterprises on system evolution is investigated, as shown in Fig. 6.

From Fig. 6, it is easy to know that this critical threshold decreases from 84.70% to 39.48% as market share $\theta$ increases from 1.4 to 2.0, which means that the system gradually evolves to equilibrium 1 at a faster speed, and Therefore, the diffusion process of GPTs becomes slightly smoother. The reason for this is that the larger the market share of diffusion enterprises is, the stronger the availability of the expected return of the diffusion strategy selected by enterprises. The market share of nonadopting GPT enterprises is eroded by adopting enterprises; as a result, the stronger the motivation of towards GPT adoption is, the more conducive it is to GPT diffusion. Thus, Summary 3 can be obtained as follows.

**Summary 3** The higher the additional revenue coefficient $\theta$ is for diffusion enterprises, the more conducive they are to GPT diffusion.

***5.2 The evolution of the GPT diffusion system with government support.***

**(1) The impact of government support on system evolution.** Keeping the other parameters the same as in Fig. 3, let $y = 0.5$, $A = 1$ and $G$ increase from 1 to 2. Therefore, when both diffusion enterprises choose the diffusion strategy, $\Delta x = \tau_{k,y} x$=$0.378 / 0.756$. When only one enterprise chooses the diffusion strategy, $\Delta x = \tau_{k,y} x = 0.30 / 0.60$, $r = 73\%$ is still used as the benchmark line for the comparative analysis. As shown in Fig. 7.

From Fig. 7, after considering financial subsidies, knowledgeand technical support (both accounting for 50% of the government's budget $G$), compared with Fig. 3, the critical threshold of the system evolves to different equilibrium and is reduced from $r = 73.11\%$ to $r = 34.06\%$ when $G$ increases to 2.0. The critical threshold decreases to $r = 17.96\%$, which means that the system evolves to equilibrium 1 with a greater probability. The reason for this is that government financial subsidies support can reduce the costs of GPT adoption for enterprises, and knowledge and technical support is conducive to promoting the success rate of commercial development, forming good market revenue expectations for enterprises and thus promoting the GPT diffusion. Thus, summary 4 can be obtained as follows.

**Summary 4** The financial subsidies, knowledge and technical support of government are conducive to the GPT diffusion.

**(2) The impact of different government supports on system evolution.** To study the change in proportion $y$ of government support and the impact of the intellectual property system on system evolution, a comparative analysis based on Fig. 7 is shown in Fig. 8.

As shown in Fig. 8(a), when the proportion $y$ of government support is reduced from 0.5 to 0.2, the government uses 20% of its budget $G$ as financial subsidies support and 80% as knowledge and technical support. Compared with the Fig. 7, Fig. 8 shows that the critical threshold of the system evolves to a different equilibrium, decreasing from $r = 34.06\%$ to $r = 29.73\%$. When the proportion $y$ of government support increases to 0.8 (as shown in Fig. 8(a)), 80% of government budget $G$ is used as financial subsidies; at this time, the critical threshold of the system evolves to a different equilibrium, which becomes $r = 58.67\%$. It is clear to see that when the increase in government financial subsidies is 60%, the critical threshold of system evolution increases by approximately 28.94%, and GPT diffusion becomes relatively difficult. This situation means that a disproportionate share of government budget dampens GPT diffusion. The next step is to analyse the impact of technology conversion coefficient $A$.

As shown in Fig. 8(b), when the technology conversion coefficient $A$ changes from 3 to 15, that is, $A$ increases by 5 fivefold. At this point, the critical threshold of the system evolves to a different equilibrium, which is further reduce to 21.16%, meaning that GPT diffusion becomes relatively easy, even with only 20% of the government budget. Otherwise, even if a large proportion of the government budget (such as 80%, as shown in Fig. 8(a)) is used for knowledge and technological support, it cannot effectively promote GPT diffusion. According to this finding, an interesting conclusion (Summary 5) can be drawn as follows.

**Summary 5** A disproportionate share of government bedget dampens GPT diffusion. The effect of knowledge and technical support on GPT diffusion is positively regulated by the technology conversion coefficient $A$.

Furthermore, the impact of the intellectual property protection of GPTs on system evolution is investigated. For this, let $e = 0$; at this time, enterprises need to pay all the intellectual property transfer fees $\pi_z = 3$ to choose their GPT diffusion strategy. As shown in Fig. 9.

It can be seen from Fig. 9(a) that when the cost coefficient $\lambda$ of GPT adoption for the enterprises changes from 0.49 to 0.7 and then to 1, compared with Fig. 7, the critical threshold of the system evolving to different equilibrium rises rapidly from 34.06% to 74.76% and then to 76.78%. Thus, at this time, the probability of enterprises choosing the diffusion strategy needs to exceed 76.78% before the system evolves to equilibrium 1. The reason for this is that the round intellectual property rights system requires enterprises to pay all adoption costs to obtain GPTs. In addition, the reduction in the share probability of supply enterprises dampens the enthusiasm of diffusion enterprises towards choosing a diffusion strategy. Then, combining Fig. 3, as shown in Fig. 9(a)-(b), when additional revenue coefficient $\theta$ increases from 1.5 to 2.0, the critical threshold of the system evolves to a different equilibrium, decreasing to 45.12%, this situation means that GPT diffusion is becoming more difficult From this, Summary 6 can be obtained as follows.

**Summary 6** The intellectual property protection system of GPTs is not conducive to their diffusion. And the additional revenue coefficient of GPTs for diffusion enterprises alleviates this kind of adverse effect.

In summary, according to Summaries 4-6, the positive effect of financial subsidies, knowledge and technical support on GPT diffusion still needs corresponding policies to ensure its effective support and implementation. In particular, there should be a trade-off between financial subsidies and knowledge and technical support, and effective policies are needed to play this role. The establishment of an intellectual property system for GPTs is not conducive to their diffusion. Therefore, the government should establish some effective supporting policies to promote GPT diffusion, such as a sharing mechanism after the government purchases GPTs.

## 6 Conclusion and Policy Suggestions

GPTs play an important role in technological progress and economic growth, which is achieved through GPT diffusion in related areas. The existing literature has fully studied the macroeconomic effect of GPT diffusion using the mainstream optimal (endogenous) model, but has neglected the GPT diffusion process itself. Considering the inapplicability of the existing mathematics model for studying GPT diffusion process, this paper analyses the GPT supply and diffusion process, builds an evolutionary game model to reveal the evolutionary mechanism of GPT diffusion and its influencing factors from the whole GPT R&D process, and also focuses on the role of government support.

The conclusions obtained in this study include multiple perspectives, such as GPT supply, adoption and commercial development; market revenue realisation; government support. (1) From the GPT supply perspective, the stronger the share probability of supply enterprises is, the greater the commonness degree is and the more reliable the technical characteristics are, the more conducive they are to GPT diffusion. (2) From the adoption and commercial development perspectives, the smaller the cost coefficient of GPT adoption is, the lower the commercial development cost is and the higher the success rate of commercial development is, the more conducive they are to GPT diffusion. (3) From the market revenue realisation perspective, the higher the additional revenue coefficient to diffusion enterprises is, the more conducive it is to GPT diffusion. (4) From the government's support perspective, government financial subsidies, knowledge and technical support are conducive to GPT diffusion. The trade-off between financial subsidies and knowledge and technical support is important. The effect of knowledge and technical support on GPT diffusion is positively regulated by the technology conversion coefficient. However, the intellectual property system is not conducive to GPT diffusion.

The government should provide supports with multiple forms, and the following can be considered in promoting GPT diffusion. First, market demand acts as traction for the high-quality supply of GPTs, which in turn affects GPT diffusion. In this context, there are some questions that need to be answered, such as whether the supplied GPTs are urgently needed by enterprises? Can GPTs be easily acquired by enterprises in need? Can GPTs be widely used (i.e., is the commonness degree large enough)? Are the technical characteristic of GPTs reliable in quality and stable in performance? If these questions are answered positively, then support by the government in multiple forms, such as finaciall subsidies, knowledge and technical support, can avoid the motivation of enterprises to seek other market opportunities to promote GPT diffusion. Second, in addition to the above forms of support, the government should also guide universities and scientific research institutes in participating in the GPT diffusion process. The government should encourage supply enterprises to share and diffuse GPTs and promote the awareness of property rights protection for enterprises and other bodies. At the same time, the government should establish a sharing mechanism of GPTs, which can be facilitated by the development of appropriate policies and their timely implementation. Third, taking multiagent cooperation as the organisational guarantee promotes efficient GPT diffusion. For example, the participation of financial institutions, universities, scientific research institutes and marketing planning institutions, which make commercial development activities run smoothly, promotes effective diffusion of GPTs and realises the potential economic and social benefits.

This study has some limitations that can be overcome by furture studies. In this work, we only incorporate the share probability of GPTs to diffusion enterprises and the technical characteristics of supplied GPTs into the game model. To comprehensively investigate the factors and mechanism of GPT supply and diffusion, we will further incorporate the supply process of GPTs and the impact of market competition after sharing GPTs to analyse in depth the dynamic evolution between the enterprises involved in GPT R&D. In addition, it will be meaningful to explore the intrinsic mechanism of the impact of GPTs on technological progress and economic growth from the both micro and macro perspectives.

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**Appendix A:**

**The proofs of Theorem 1.** Assume that $f(r) = r(1-r)(\Delta_3 r + \Delta_4)$, and that $f(r^0) = 0$, i.e., $r^0$ is the equilibrium point of $f(r)$. Let $f(r)$ be a Taylor expansion at point $r^0$, and then, taking only one term, Eq. (5) can be approximated to [illegible]$(r - r^0)$, where $f'(r^0) = (1-2r^0)(\Delta_3 r + \Delta_4) + r^0(1-r^0)\Delta_3$. Therefore, the ESS of Eq. (5) can be obtained as follows:

When $r^0 = 0$, $f'(0) = \Delta_4 < 0$; that is, $r^0 = 0$ is the ESS point in Eq. (5);

When $r^0 = 1$, $f'(1) = -(\Delta_3 r + \Delta_4)$, and because $\Delta_3 r + \Delta_4 > 0$, $f'(1) < 0$, $r^0 = 1$ is the ESS point in Eq. (5);

When $r^0 = -\frac{\Delta_4}{\Delta_3}$, $f'(-\frac{\Delta_4}{\Delta_3}) = -\Delta_4(1-\frac{\Delta_4}{\Delta_3})$, and because $\Delta_4 < 0$, $f'(-\frac{\Delta_4}{\Delta_3}) > 0$, and since equilibrium point $-\frac{\Delta_4}{\Delta_3}$ is between 0 and 1, $-\frac{\Delta_4}{\Delta_3}$ is the saddle point of the evolutionary instability in Eq. (5).

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