Tracking the dynamic technological development by exploring the sciencetechnology linkage: From the perspective of technology life cycle
Introduction

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The science-technology (S-T) linkage emphasizes the knowledge transmission between technological invention and basic science research, which is an intertwined and evolving interactive relationship that has promoted in-depth scientific exploration and the emergence of technological revolution. Previous efforts toward exploring the technology innovation process by the S-T linkage have focused on discussing the relevant profiles of technology developers, such as the R&D tendencies for specific technologies at the national levels or technology itself (Fan, Liu, & Zhu, 2017; Tijssen & Winnink, 2018), identifying the core scientific fields in different technological fields (Chang, 2018), exploring the behavior of S&T interaction, etc. However, the fact that technological innovation is a dynamic process with a certain life cycle has been overlooked in current studies. And due to the correlations and heterogeneity between scientific and technical knowledge (Xu, Li, An, Hao, & Yang, 2021), it is helpful to explore the linkages between the two in their technology life cycle (TLC) to further explore the innovation process of technology.

Artificial intelligence is considered a cutting-edge technology that is increasingly driving developments and innovations in a wide range of scientific, technological, business, and government fields. The domain is experiencing a worldwide surge in attention from policymakers, universities and institutes, corporations, and the public. Therefore, this paper takes Artificial intelligence as a case to explore the S-T linkage in each development stage of its TLC, aiming to answer the following lines of research questions: (1) How has the S-T linkage, both science linkage and technology linkage, changed over the technology life cycle? (2) Which subtechnologies or research domain is the S&T linkage focus on, has there been some shift with technological advances? (3) How S&T linkage manifests itself in scholars, whether the technological improvement will trigger some significant changes?

Framework and methodology

For the purpose of tracking the S-T linkage in the artificial intelligence (AI) technology life cycle, as shown in Fig1, our research framework consists of three phases.

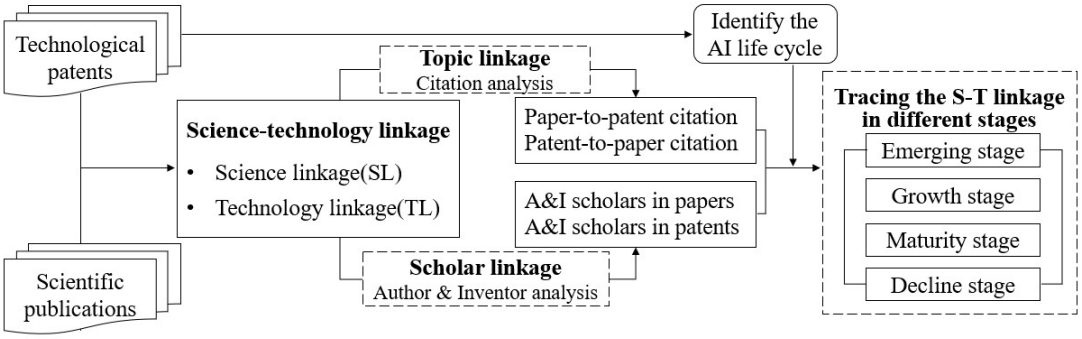

Fig.1 Research framework to explore the S&T linkage in TLC

The first step is to identify the TLC in AI to provide a better understanding of the relationship between the S-T linkage and AI development after getting the overall technical picture. We here applied the online analytics tool - Loglet Lab inputting the cumulative publication patent number to assist the AI technology life cycle. In the second phase, the science linkage (SL) and technology linkage (TL) are discussed in terms of both topic and scholar respectively. The topic linkage is to probe the S-T interactions arising from the inheritance and development of AI technology itself. While the scholar linkage is to find the key forces in facilitating this interaction. The third phase involves tracking the SL and TL changes in topic and scholar over the AI technology life cycle. For data collection, the papers are taken from Web of Science Core Collection, while the patents are extracted in Derwent innovation index (DII). To ensure the quality of the research data, we searched and compared the search results of many relevant studies and reports on AI technology and ended up quoting the search terms from the research (Liu, Shapira, & Yue, 2021). Finally, we collected the raw data on 5 July 2022, and there is a total of 91,306 papers and 164,560 patents. After data cleaning and data pre-processing, we obtained 89,644 papers and 164,560 patents.

As shown in Fig.1, the S-T linkage was quantified in the topic and scholar parts. For the former part, the linkage was constructed by using paper-to-patent citation and patent-to-paper citation. For the latter, the linkage is formed by identifying the scholar being both author and inventor.

Findings and conclusions

We identified the science and technology act as the “dancing partners” (de Solla Price, 1965), an overall co-progressive relationship. Both the topic linkage and the scholar linkage in TL and SL, are strengthening in AI cycle-life and significantly more in the growth stage (2016-2020) than in the emerging stage (1971-2015). Our analysis of S&L linkage shows the science linkage in the topic becomes stronger as technology advances when AI enters the growth stage, while the technology linkage in the topic is not. At the scholar linkage, the annual number of these scholars is growing over time with more notable in the growth stage. For their research interests, there is a central tendency accompanied by a certain degree of shift in the period 2018-2020.

Our results, the analysis of TL in the topic (Fig.2), indicated that the reliance on technology in basic science research becomes stronger as technology advances. While the SL showed the link with basic scientific research is important but does not strengthen as the technology moves forward (Fig.3). Moreover, both the SL and TL changes over time placed much emphasis on

the specific year 2016, the period for AI technology to enter its second stage of development. However, the SL demonstrated signs of decline according to the patent-to-papers citations after 2018, even with the TCL showed that this stage will remain there until 2023. This result may suggest that AI advance into the next stage (The maturity stage) will depend heavily on the specific technology inventions, not the basic scientific research. Moreover, certain changes will occur when AI enters its second stage of TLC. For example, the number of papers citing patents in the research domain *Engineering, Electrical & Electronic* experienced a significant increase in 2020 with an increase of more than 150%.

Our findings in scholar linkage reveal that (Fig.4), similarly, the steadily increase before 2016 in the number of these scholars and their papers and patents and with a noticeable growth thereafter. Possible explanations for this could be the shared demands for scientific and technological knowledge. The investigation of the performance of these scholars' papers and patents indicated that they have published more papers in parallel with their technological inventions. In addition, there also have been some changes in these scholars' research topics with AI advances specifically in technology inventions. For example, a descending trend of the educational aids (T01-J30A), on-line education (T01-N01B3), and image analysis (T01-J10B2) suggest a shift in their focus.

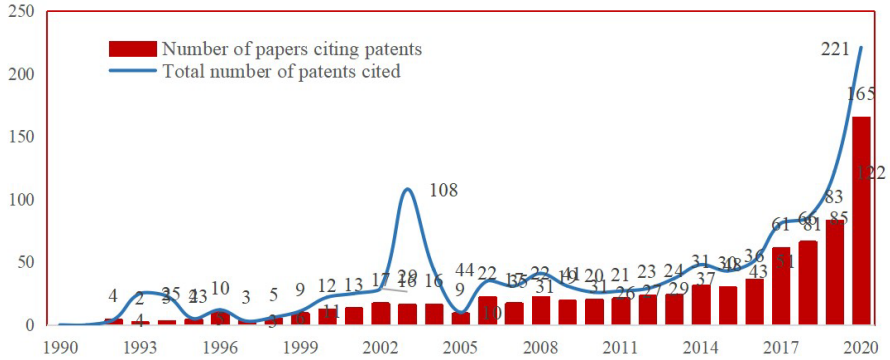

Fig.2 The TL in topic linkage over 1990 to 2020

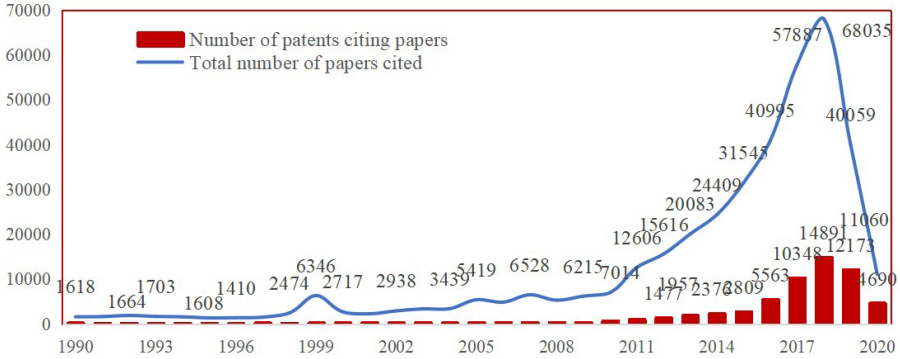

Fig.3 The SL in topic linkage over 1990 to 2020

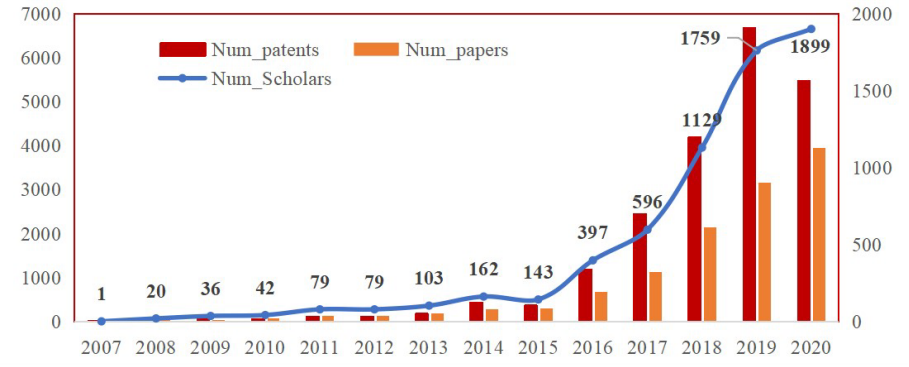

Fig.4 The distribution of the author-inventors from 2007 to 2020

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