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Divergence of knowledge production strategies for emerging technologies between late industrialized countries: Focusing on quantum technology

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Abstract

Traditional wisdom on how late industrialized countries follow the technology trajectories of preceding economies is in need of reformation as these countries have attained industrial leadership in a growing number of fields. However, current understandings about these countries' development of their emerging technologies have yet to investigate the divergence of idiosyncratic technology trajectories. The aim of this paper was to explore how their knowledge production strategies in emerging technology sectors are diverging. Specifically, this research examines the changing patterns of knowledge production in quantum technology in South Korea and China by developing a knowledge portfolio and knowledge strategic diagram. According to the knowledge portfolio, the relative literature position differs. In the knowledge strategic diagram, there are diverging patterns in the emerging keywords sector. This paper contributes to the literature by demonstrating the diverging strategies of late industrialized countries in their transition from catch-up to post-catch-up paradigms and provides policy implications for countries developing an idiosyncratic trajectory in emerging technology sectors.

KEYWORDS

emerging technologies, knowledge production strategies, late industrialized countries, quantum technology

1 | INTRODUCTION

Because of the prospects of high social impact and increased probability of successful commercialization, the research and development (R&D) investment in quantum technology has been rapidly and globally increasing. Specifically, this technology is expected to have a remarkable influence on fields such as optimization, information processing, cryptography, and analytics. According to *Technology Review* from the Massachusetts Institute of Technology, "practical quantum computer" was selected as one of top 10 innovation technologies because of its expected impact across a broad field of industries such as information communication, chemistry, and biopharmaceuticals [1].

Similar to advanced countries such as the USA, the Netherlands, and the UK [2], late industrialized countries such as South Korea and China have also started to pioneer in the emerging sector, which is a contrast to the traditional wisdom from the existing literature on catch-up theories. The core strategy of the late industrialized countries was to conduct catch-up strategies and become specialized in an existing market such as semiconductors [3–5], displays [6], or biopharmaceuticals [7]. However, unlike the industries in which they have specialized, quantum-related industries still include high technology and market uncertainties [2]. This is the stage of evolving from catch-up paradigm to post catch-up paradigm, as those late industrialized countries start to transform themselves from imitators to innovators [3,4,8,9].

Another distinguishable strategic feature shown in the knowledge production strategies of quantum technology is that the R&D strategies of the two late industrialized countries are diverging. China has announced it will target the attainment of global leadership in quantum technology itself. The country has put a huge amount of investment in and promoted coordination among the private sector, public research institutes, and universities. On the other hand, South Korea tends to consider the development of quantum technology as one instrument for achieving national long-term planning strategies in the information and communications technology (ICT) sector, and most research is conducted by public research institutes and universities separately [10–13]. This divergence in strategies is also in contrast to the previous literature demonstrating that China followed or applied development trajectories of prior late industrialized countries such as South Korea or Taiwan [13,14].

In order to explain the discrepancy between the observed phenomenon and extant literature, this paper developed the following research questions: How are the late industrialized countries specializing themselves in emerging technologies where there is high market and technology uncertainty? Moreover, how are their knowledge production strategies diverging? Even though China has followed South Korea's development trajectory in the past, different development models are expected for emerging technologies in the two countries when considering institutional dynamics and market size [15]. Thus, this paper aims to examine and compare the features of knowledge production of emerging technologies in the late industrialized countries. In detail, this paper focuses on how South Korea and China have developed their knowledge portfolios [16] and strategic diagrams [17] in the three sub-fields of quantum technology, quantum computing, quantum sensor/imaging, and quantum communication. This paper is expected to contribute to the literature on catch-up theories by expanding the research on how late industrialized countries that based their core strategies on catch-up strategies evolve and diverge after the catch-up paradigm.

The remainder of this paper is structured as follows: Section 2 briefly reviews the literature on the knowledge production strategies of late industrialized countries. Section 3 demonstrates research methodologies for data analysis, and Section 4 presents the result of the data analysis. Sections 5 and 6 summarize and discuss the result and provide its implications.

2 | LITERATURE REVIEW

The success of the late industrialized countries in East Asia (such as South Korea, Taiwan, and Singapore) has presented an academic conundrum because their achievements and progress in gaining innovative prowess were not founded on traditional approaches to innovation [18]. Later, successful innovation activities in those late industrialized countries have been attributed to catch-up strategies. The catch-up strategies follow the reverse direction in a technology trajectory as the countries accumulate innovation capabilities through assimilating, adapting, and modifying the existing technologies at a mature stage [19–21].

After the successful catch-up period, those countries modified the knowledge production strategies, from imitation to innovation. The transition from imitator to innovator required different capabilities from those in the catch-up period as not only the uncertainty of transition is unknown, but uncertainties about the technology and market are very high because the late industrialized countries need to pioneer the new sectors and develop new trajectories [22]. Thus, the term "post catch-up" was developed to indicate the evolution of a catch-up paradigm and is expressed as *"innovation activities in which the latecomer countries establish new technological trajectories for innovation in a changing competitive environment where scarce opportunity for imitation is present"* [9].

The late industrialized countries showed three patterns of evolving from the catch-up paradigm: (1) "path-following" indicates following the same path (taken by advanced countries) over a shorter period; (2) "stage-skipping" describes following some stages while skipping others to save time; and (3) "path creating" suggests that the late industrialized countries explore and develop their own technological trajectories [8].

Although there are different patterns of catch-up, as aforementioned, one of the commonly shared features shown by the late industrialized countries (and distinct from advanced countries) is that they have exclusively limited their technological scope and accentuated the increase of production to overtake leadership in the global markets that were in an industrial downturn [16,23,24]. For example, the late industrialized countries (such as South Korea and Taiwan) implemented intense innovative activities in the thin-film transistor-liquid crystal display (TFT-LCD) industry when it was in a downturn, and similar patterns were shown in the semiconductor industry, where South Korea, Taiwan, and China entered during the fourth, fifth, and sixth downturns, respectively [6,25,26]. These analogous entry strategies were shown in other industries, where late industrialized countries have attained leadership, such as in the automobile, electronics, steel, or solar PV cell industries [27–29].

Because of this peculiar feature of the late industrialized countries' concentration on industrial downturns, previous studies have explained how these countries were able to overtake industrial leadership in the existing markets or industrial sectors [5,16,25,30–35]. This implies that there are few studies on knowledge production strategies for emerging technologies with high market and technology uncertainties, where no industry has yet been established. This gap needs to be filled because the late industrialized countries are expected to develop their own technological trajectories with scarce reference in forming a novel paradigm [36].

3 | RESEARCH METHODS

3.1 | Research framework

Although the number of firms conducting R&D activities on quantum technology is increasing, more time is still needed to resolve the technology and market uncertainties. No firm has yet succeeded in commercialization, and most related knowledge stems from basic or applied research [2,12]. Even with the high uncertainties in the technology and market, the late industrialized countries have started to conduct R&D activities to develop quantum technology. However, two representative countries, South Korea and China, are showing different attitudes toward these activities. Hence, the research questions piloting this study are narrowed down as follows: In which fields of quantum technology are South Korea and China specializing? Moreover, in which knowledge domains are the two countries specializing? Thus, this paper is dedicated to examining knowledge specialization by applying the frameworks of the knowledge portfolio [16] and knowledge strategic diagram [17].

A knowledge portfolio (or technology portfolio) is recognized as an instrument to evaluate the innovation capabilities of a nation or a firm in a specific industry. Traditional portfolios were evaluated based on the judgments of experts, but patent data started to be used to develop technology portfolios more objectively [37,38]. Similarly, publication data were used to develop knowledge portfolios [39,40].

In contrast, a knowledge strategic diagram is widely used to examine the structure of knowledge or capabilities based on co-occurrence keyword analysis techniques. According to such a diagram, four clusters are classified according to network structure [17,41] or growth rate [42-44]. The former method is used to identify major keywords from their relationships, whereas the latter is used to identify promising (or declining) keywords. Because the aim of this paper is to examine how late industrialized countries respond to emerging technologies, this paper adopted the latter approach, as shown in Figure 1.

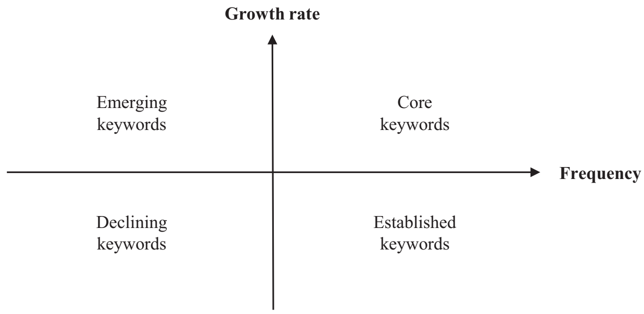

FIGURE 1 Knowledge strategic diagram

We assumed that the frequency of using a certain keyword implies the extent of interest among researchers. Thus, if the frequency of a certain keyword increase, it indicates that research topics related to the keyword are becoming increasingly important. To elaborate, keywords are classified into "core keywords" if both the frequency and growth rate are high and considered to be incessantly important research areas. "Emerging keywords" denotes emerging areas because their frequency is low but growth rate is high. On the other hand, keywords that are classified as "established keywords," which have high frequency but low growth rate, indicate a mature stage of research

In order to examine how the knowledge production patterns of South Korea and China have developed over time, this paper divides the periods into three phases according to the incidents that represent increased interest in quantum technology. The first phase lasted until 2005, which was when both countries announced they would conduct quantum-related national R&D programs [1,10]. The second phase ranges from 2006 to 2011, when public-led R&D programs were intensified. Around this period, many countries, including South Korea and China, announced they would implement long-term R&D projects to develop quantum technology [1]. In addition, at the end of the second phase, in 2012, IBM first announced the possibility of commercializing the technology [2]. From this feature, we determined the third phase to be between 2012 and 2018. In the third phase, late industrialized countries supposedly began to show greater interest. Hence, we analyzed how the knowledge portfolio and knowledge strategic diagram have changed according to these three phases.

3.2 | Data collection

In order to analyze knowledge production strategies, this study used bibliometric data provided by the Web of Science

(WoS). The database from the WoS contains extensive bibliometric data such as journals, titles, keywords, research areas, and so on. Quantum technology is an emerging technology, and it cannot be classified into any research area or journal category of WoS. Hence, although retrieving data based on journal categories might allow more precise data [45], this paper developed search queries. In order to determine the main keywords for the search queries, we conducted interviews with relevant experts. Since November 2018, we conducted a series of interviews with professors and graduate students from the Korea Advanced Institute of Science and Technology who were conducting research on quantum technologies. Referring to previous literature of examining research trends on quantum technology [46,47], this paper classified the technology into three categories, computing, sensor/imaging, and communication, and developed three search queries for each category based on these interviews with the experts. The data retrieval date was August 30, 2019.

After retrieving data based on the search queries, we further limited our scope to papers that were published by authors from South Korea and China. In addition, to investigate their pattern of divergence, we included published papers from seven other advanced countries (the USA, Germany, the UK, Japan, Canada, Australia, and the Netherlands) who are the leading nations in quantum technology according to our follow-up interview with the experts. In this paper, to investigate how the two late industrialized countries diverge, we divided advanced countries into two groups according to the total amount of R&D investment per year. This paper did not use the amount of R&D investment spent on quantum technology, because no such data were available. Thus, in this paper, it was assumed that advanced countries with a relatively large amount of resources are the USA, Germany, and Japan (Group 1), whereas the others are classified as the those with a low amount of resources (Group 2).

3.3 | Analysis methods

3.3.1 | Knowledge portfolio

Referring to previous literature [16], in order to develop a knowledge portfolio, this paper measured two elements, revealed literature advantage (RLA), and relative literature position (RLP). The RLA can be measured using the following equation [36]:

$$\mathrm{RLA}_{ij} = 100 \times \tanh\left(\ln\left(\frac{N_{ij}/\sum_i N_{ij}}{\sum_j N_{ij}/\sum_{ij} N_{ij}}\right)\right), \quad (1)$$

where N_{ij} refers to the number of published papers in technology field j by country i, and the RLA has values between −100 and +100. A high value of RLA indicates a higher degree of knowledge specialization of a certain country, and if the value of two countries differs by more than 15, then it implies that there is a significant difference between the two [16,37].

Next, RLP can be measured as follows:

$$\mathrm{RLP}_{ij} = \frac{N_{ij}}{\max_{i \in n} N_{ij}}, \quad (2)$$

where n implies the total number of the analyzed countries. RLP is used to reveal the proportion of a country in a certain technology field globally. Accordingly, a country that publishes papers in a certain technology field the most becomes the reference point, implying that the maximum value of RLP is 1 [16].

When analyzing a knowledge portfolio, control variables such as the amount of annual investment or number of researchers were not considered because it was difficult to get related data. Instead, advanced countries are grouped into two according to the amount of R&D budget to examine whether the difference between South Korea and China follows the amount of available resources. This approach seems plausible, because knowledge portfolios are widely developed using bibliometric data without other control variables [16].

3.3.2 | Knowledge strategic diagram

As aforementioned, the knowledge strategic diagram consists of four categories, characterized by the indices of frequency of occurrence and growth rate of a certain keyword. Instead of using general frequency and growth rate, this paper adopted an approach that normalizes the values. Thus, this paper applied the formulas of normalized performance index (NPI) and normalized growth index (NGI) because they are more sophisticated formulas obtained by normalizing the index of frequency and growth rate [42]. The formulas of NPI and NGI are as follows:

$$\mathrm{NPI}_a = \frac{\log \mathrm{TP}_a - \sum_{i=1}^{n} \frac{\log \mathrm{TP}_i}{n}}{\sigma}, \quad (3)$$

$$\mathrm{NGI}_a = \frac{\mathrm{GI}_a - \sum_{i=1}^{n} \mathrm{GI}_i / n}{\sigma}, \quad \mathrm{GI}_a = \frac{\sum_{i=1}^{\mathrm{TP}_a} py(i) / \mathrm{TP}_a - \mathrm{BY}}{\mathrm{EY} - \mathrm{BY}}, \quad (4)$$

where TP_a refers to the total number of published papers with keyword a, and n refers to total number of keywords that are analyzed. Further, $py(i)$ refers to the published year of the ith paper, and EY and BY refer to the first and last years of published papers with keyword a.

4 | ANALYSIS RESULT

4.1 | Overview

Table 1 demonstrates the overall research trend of each classification of quantum technology. The research area of quantum communication contains cryptography, transmission, and networks. Building on the introduction of the quantum key distribution protocol [48], the USA and England started to publish papers in the early 1990s. Later, in the late 1990s or early 2000s, other countries, including South Korea and China, started to publish papers. Since phase II, China has started to lead the production of quantum communication-related knowledge by publishing 2527 papers at an average annual growth rate of 21.1%. On the other hand, South Korea has published 236 papers with an average annual growth rate of 11.2%, whereas all other advanced countries except for the USA, have published 485.5 papers on average, with an average annual growth rate of 11.9%.

Quantum measurement, quantum sensing, and quantum imaging are included in the field of quantum sensors/imaging. The total amount of global production of this field is relatively small because it has only recently received attention [49,50]. Unlike quantum communication, South Korea made relatively less effort to create related knowledge by having an average annual growth rate of 11.1%, whereas China had a rate of 19.9% and the others had a rate of 20.4%. Until phase II, the USA produced almost half of the quantum sensor/imaging-related papers (44.9%). However, in phase III, China created almost twice as many as the USA by publishing 710 papers, whereas the USA published 387 papers.

Since the effect of quantum mechanics on computation was proposed [51,52], the studies in the literature have conducted research on quantum simulators, physical quantum bits, logical quantum bits, and quantum software. While initial studies were conducted in the USA and Japan in 1980s, other countries started their research in late 1990s as the first quantum algorithms were developed [53,54]. Unlike the other subtechnologies, China produced fewer quantum computing related papers than the USA in all three phases. In addition, no other country published fewer papers than South Korea. South Korea published 120 papers, whereas the others published 539.7 on average.

TABLE 1 Research trends in quantum technology

Phase	Classification	KOR	CHN	USA	Others
I	Communication	39	302	339	516
	Sensor/imaging	12	8	101	95
	Computing	16	81	568	699
II	Communication	80	932	447	901
	Sensor/imaging	17	92	197	142
	Computing	27	226	528	840
III	Communication	117	1595	798	1496
	Sensor/imaging	37	710	387	524
	Computing	77	826	1199	1699

Quantum computing-related papers were published earlier than the other two fields, and until 2018, 6786 (40.7%) papers were published. Although papers related to sensors/imaging and communication began to be published during a similar period, until 2018, the number of publications is quite different: 2322 (13.9%) and 7562 (45.4%), respectively.

The production of knowledge related to quantum computing began earlier than for the other two fields, and the USA led the knowledge production in all three fields in the first phase. China began to produce a significant amount of publications during the early 2000s in the fields of computing and communication, and also started to intensively publish on sensors/imaging in the late 2000s. Despite having started later, China was able to overtake the USA as the largest producer of publications in the two fields of sensors/imaging and communication. However, in case of South Korea, although they started to produce quantum-related knowledge at similar time as China, the amount of production is relatively low.

4.2 | Knowledge portfolio

4.2.1 | Computing

According to Table 2, when compared with the other advanced countries, both South Korea and China have a relatively lower weight in their portfolios for computing. In total, only South Korea and China had negative RLA values, and they are significantly different from the others. Moreover, the RLAs from all three phases had negative values for the two countries, while no other countries showed negative values of RLA in phase II and phase III. Germany, the UK, and Australia showed negative values also, but the extent of specialization is still significantly different with respect to the late industrialized countries.

Although the RLA showed similar patterns, the patterns are diverging in RLP. The RLP of South Korea and China were 0.028 and 0.140, respectively, in phase I. Each value is the lowest when compared with the other advanced countries with similar amounts of R&D investment. However, while South Korea had an RLP of less than 0.1 in all three phases, China showed an increase from 0.140 (phase I) to 0.688 (phase III).

The results indicate that both late industrialized countries strategically put a lower emphasis on computing, because it takes relatively much more time and cost to catch up. However, China tends to produce more than other countries, while the proportion of international publications of South

TABLE 2 Knowledge portfolio of quantum computing

Phase	Knowledge portfolio	KOR	CHN	Group 1			Group 2			
				USA	GER	JAP	AUS	ENG	CAN	NTL
Total	RLA	−26.945	−41.772	29.270	10.140	38.693	7.833	9.034	30.632	40.376
	RLP	0.052	0.491	1.000	0.323	0.412	0.125	0.227	0.235	0.083
I	RLA	−55.938	−63.562	20.194	−5.434	33.063	−9.745	−5.343	29.771	35.346
	RLP	0.028	0.140	1.000	0.236	0.503	0.076	0.193	0.138	0.067
II	RLA	−39.417	−53.333	32.571	18.497	46.890	14.670	8.414	41.862	36.662
	RLP	0.051	0.429	1.000	0.348	0.505	0.136	0.230	0.303	0.068
III	RLA	−12.475	−32.681	30.177	11.677	34.260	10.536	13.983	27.198	41.609
	RLP	0.063	0.688	1.000	0.355	0.328	0.145	0.242	0.253	0.096

TABLE 3 Knowledge portfolio of quantum sensor/imaging

Phase	Knowledge portfolio	KOR	CHN	Group 1			Group 2			
				USA	GER	JAP	AUS	ENG	CAN	NTL
Total	RLA	1.493	10.670	5.623	−18.214	−39.842	−10.683	−31.035	−48.468	−31.328
	RLP	0.081	1.000	0.917	0.285	0.211	0.122	0.176	0.118	0.046
I	RLA	33.763	−94.626	16.740	−20.395	−35.689	−12.537	−16.717	−3.140	−56.275
	RLP	0.076	0.051	1.000	0.210	0.255	0.076	0.178	0.102	0.025
II	RLA	17.496	−41.878	38.648	−51.968	−34.754	−18.040	−71.187	−27.607	15.837
	RLP	0.086	0.465	1.000	0.152	0.197	0.091	0.081	0.136	0.051
III	RLA	−13.025	22.133	−10.047	−9.862	−36.337	−10.459	−21.631	−63.528	−42.376
	RLP	0.052	1.000	0.547	0.236	0.129	0.097	0.139	0.075	0.032

Korea is similar to advanced countries with relatively low resources (such as Australia or the Netherlands).

4.2.2 | Sensors/Imaging

According to Table 3, in total, the RLA of South Korea and China had positive values, while most other advanced countries (except the US) showed negative values. However, the RLA of South Korea decreased from 33.763 to −13.025, while that of China increased from −94.626 to 22.133.

In the case of RLP, a similar pattern is shown in the quantum computing field. While the RLP of South Korea was very low (lower than 0.1 in all three phases), the RLP of China increased from 0.051 (phase I) to 1 (phase III).

The result implies that both late industrialized countries strategically started to produce sensor-imaging related knowledge because it is relatively easier to catch-up due to the short cycle. However, while South Korea strategically specialized in the field, their proportion began to decrease. On the other hand, China had shown little interest in the field in the early phase, but started to produce the related knowledge intensively and achieved a higher proportion after phase I.

4.2.3 | Communication

Both late industrialized countries were highly specialized in the field of quantum communication, and the RLAs of communication are significantly higher than the RLAs of the other fields. Moreover, unlike other fields, both countries showed positive values of RLA in all three phases. This pattern is significantly distinguishable from the patterns of other advanced countries, where no country had a positive value of RLA since phase I (except for the UK in phase II).

As shown in Table 4, similar to quantum computing, while the two countries show a similar pattern for RLA, different patterns are shown for RLP. Similar to the RLPs other fields, the RLP of South Korea decreased from 0.115 (phase I) to 0.074 (phase III), whereas RLP of China increased from 0.891 (phase I) to 1.000 (phase III).

RLA and RLPA have opposite values in the case of the Chinese communication portfolio, whereas the others have the same direction. This may be due to the fact that even when China is putting less emphasis on creating communication-related knowledge, its total amount of created work is still much higher than any other country.

The result implies that similar to previous catch-up strategies, both late industrialized countries strategically

TABLE 4 Knowledge portfolio of quantum communication

Phase	Knowledge portfolio	KOR	CHN	Group 1			Group 2			
				USA	GER	JAP	AUS	ENG	CAN	NTL
Total	RLA	35.136	40.606	−10.953	17.966	−11.762	19.478	21.306	6.690	−13.326
	RLP	0.084	1.000	0.562	0.297	0.207	0.120	0.218	0.155	0.040
I	RLA	26.622	52.429	−30.550	8.899	−39.831	12.019	10.123	−42.219	−37.140
	RLP	0.115	0.891	1.000	0.459	0.394	0.159	0.379	0.109	0.053
II	RLA	13.731	27.469	−35.002	−4.302	−35.562	−2.544	6.706	−28.349	−37.830
	RLP	0.086	1.000	0.480	0.268	0.203	0.111	0.219	0.141	0.030
III	RLA	13.059	13.413	−26.685	−4.497	−22.758	−3.250	−5.978	−1.582	−27.337
	RLP	0.074	1.000	0.504	0.273	0.164	0.114	0.179	0.170	0.042

specialized in a technological field where they can more easily catch up due to its short cycle. However, while China is more actively creating quantum-related knowledge, South Korea is relatively passive.

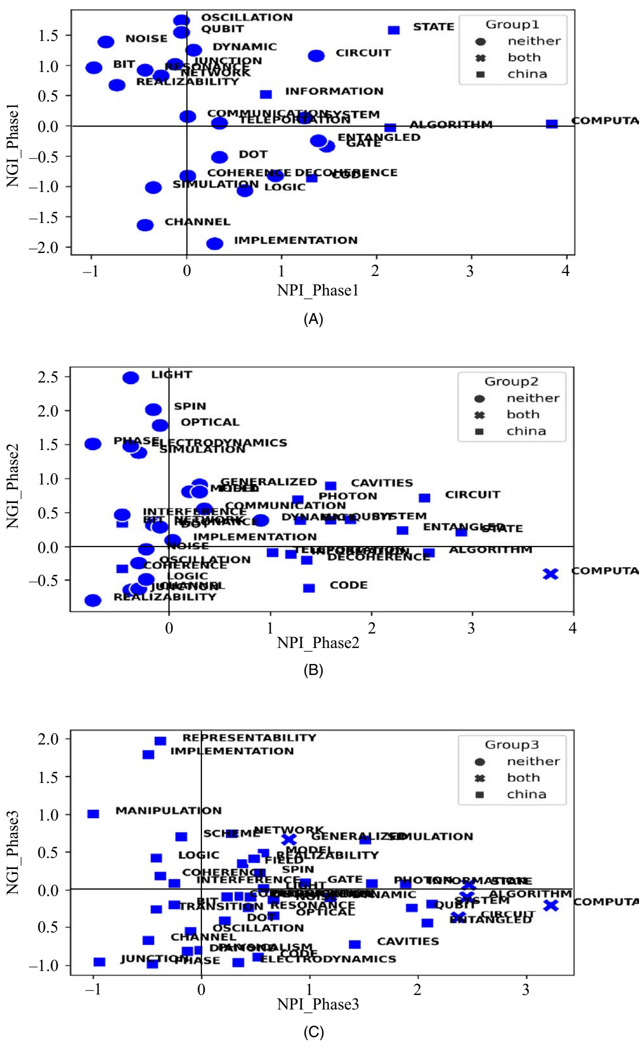

FIGURE 2 Knowledge strategic diagrams of quantum computing in (A) phase I, (B) phase II, and (C) phase III

4.3 | Knowledge strategic diagram

The knowledge strategic diagrams are developed with keywords that were globally used more than 10 times and listed in the top 100. For a clearer view of the results, the selected keywords that were used either by China or by South Korea in phase III were used to draw the diagrams in the figures.

The shapes of the markers show whether China or South Korea created a certain keyword. A circle implies that neither China nor South Korea created that keyword. A square implies a keyword only created by China, while an "x" implies a keyword created by both countries. Because there were no keywords created by South Korea but not created by China, there is no designated marker shape for keywords that were only created by South Korea.

4.3.1 | Computing

Figure 2 shows the result of the knowledge strategic diagram in the quantum computing field. In phase I, eight keywords were classified into the "core knowledge" domain, and three of them, *computability*, *state*, and *information,* were also used by China. Two established keywords, *algorithm* and *code*, were also created by China. In contrast to the keywords used by China, no keyword was used by South Korea.

In phase II, the number of emerging and core keywords increased to 11 and 14, respectively, while the number of established keywords decreased to six. Keywords such as *state*, *circuit*, and *system,* remained in the core knowledge domain while others such as *computability*, *information*, and *teleportation* moved to the "established knowledge" domain. While South Korea created one established keyword, *computability*, China created eight core keywords, *state*, *circuit*, *qubit*, and *gate,* and six established keywords, *computability*, *algorithm*, and *code*.

In phase III, the number of emerging and core keywords decreased to 7 and 12, respectively, whereas the number of

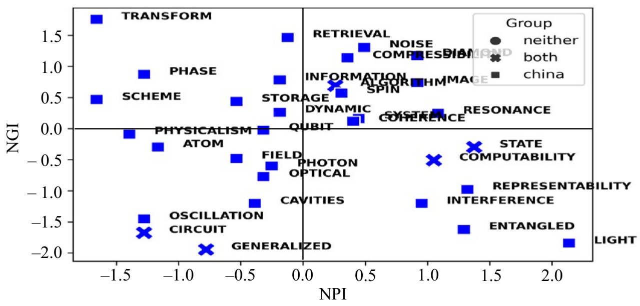

FIGURE 3 Knowledge strategic diagram of quantum sensors/imaging

established keywords increased to 17. The increase in the number of established keywords is observed because keywords such as *circuit*, *system*, *dynamic*, and *qubit* moved to the established knowledge domain. Whereas all globally used keywords were also used by China, only two core keywords, *state* and *generalized*, and three established keywords, *circuit*, *computability*, and *algorithm*, were used by South Korea.

4.3.2 | Sensors/Imaging

In case of quantum-related sensor/imaging knowledge, too few keywords that fit the condition for analysis aforementioned were used to develop knowledge strategic diagram. Thus, in this paper, only the knowledge strategic diagram for sensor/imaging in phase III was developed, as shown in Figure 3. In phase III of the sensor/imaging field, China was involved in creating core keywords such as *resonance*, *image*, and *coherence* along with emerging keywords such as *retrieval*, *dynamic*, and *transform*. However, in the case of South Korea, only five keywords were used, one core keyword, and two declining and established keywords.

4.3.3 | Communication

Figure 4 shows the result of knowledge strategic diagram in the quantum communication field. In phase I, from 44 keywords, the number of keywords that were classified into the emerging, core, and established domains were 19, 19, and 5, respectively. Keywords such as *teleportation*, *cryptography*, *Bell theorem*, and *decoherence* were classified into the core domain, and keywords such as *key distribution*, *memories*, *coherent state*, *deterministic*, and *teleportation* were classified into emerging knowledge. Two core keywords, *teleportation* and *state*, and one established keyword, *Podolsky Rosen channel*, were also created by South Korea. In the case of China, ten core keywords, including *state*, *teleportation*, *entangled*, *cryptography*, *channel*, *Bell theorem*, and *continuous variable* were use along with one established keyword, *Podolsky Rosen channel*.

In phase I, the number of keywords listed as emerging decreased to seven, whereas the number core and established keywords increased to 20 and 10, respectively. Keywords such as *atom*, *channel*, *decoherence*, and *state* moved from the core domain to the established domain, and keywords such as *key distribution*, *memories*, and *network* moved from the emerging domain to the core domain. All keywords in the core and established domains were used while emerging keywords such as *coherence*, *entangled state*, and *noise* were used by China. On the other hand, only two core keywords, *entangled* and *computability*, and one established keyword, *state*, were used by South Korea.

In phase III, the number of core and emerging keywords decreased to 13 and 5, respectively, whereas the number of established keywords increased to 15. In phase III, all globally used keywords were also used by China, including emerging keywords such as *Bell inequalities*, *entangled state*, and *resonance*. On the other hand, only four established keywords such as *communication* and *cryptography* were used along with two core keywords, *entangled* and *information*, by South Korea.

5 | SUMMARY AND DISCUSSION

The result of the knowledge portfolio implies that both late industrialized countries strategically put more emphasis on short-cycle technologies. Quantum computing is considered a long-cycle technology while the others are considered short-cycle technologies for the following reasons. First, quantum computing is more related to hardware-based technologies while the others are more software based [55]. Moreover, an interviewee said that:

> *In quantum technologies, it takes much more time and cost to catch up in the hardware-based technologies, and it is already a red ocean. However, catching up in the software-based research field is relatively easier. It should take about a year to catch up whereas it would take at least four years in hardware-based-quantum computing.*

Second, quantum communication and quantum sensors/imaging contain technologies in applied or development research whereas most technologies in quantum computing are in basic research. For example, in the case of quantum communication, a quantum key distribution network is applied research or experimental development. Further, quantum sensor/imaging technologies such as single photon sensing and photon based quantum imaging are also applied research or experimental development. On the other hand, in quantum computing, most technologies such as ultra-cold trapped ions

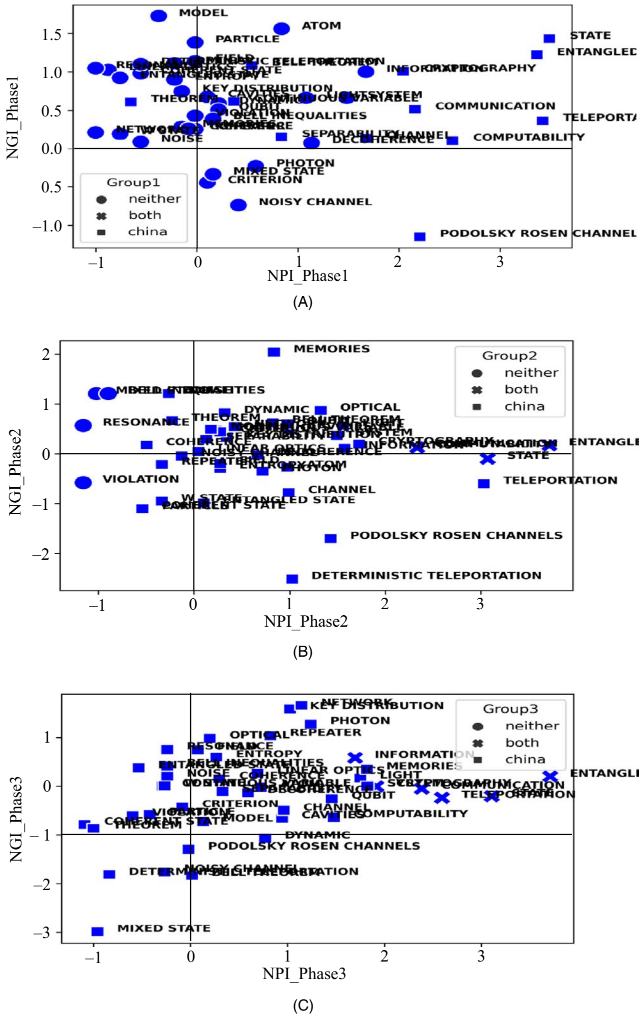

FIGURE 4 Knowledge strategic diagrams of quantum communication in (A) phase I, (B) phase II, and (C) phase III

or fault-tolerant quantum computing are considered basic research [55]. Because of these technology cycles, the technology gaps in quantum communication and quantum sensor/imaging are 2.7 years and 3.2 years, respectively, while the gap in quantum computing is 5.8 years [56].

It is consistent with previous literature that the late industrialized countries have been focused on implementing catch-up strategies in short-cycle technologies. This is because absorbing recent knowledge is relatively more important in short-cycle technologies, while accessing and accumulating old knowledge, which takes much more time and cost, is a prerequisite for developing long-cycle technologies [57].

However, the result of the diverging portfolios is in contrast to existing literature on catch-up theories, arguing that during the catch-up process, South Korea followed Japan, and later China followed South Korea [6,27,58]. This might be because of the relationship between technology specialization and the feasible amounts of resources in each country. While the distribution of created knowledge in large countries covers broad sectors, smaller countries limit their scope in target sectors [59,60]. From a resource based view (RBV), it is recommended for countries to engage in diverse topics to develop new innovation capabilities as the diverging capabilities will promote opportunities for utilizing knowledge and increasing profit [61,62]. However, RBV does not consider the cost to create the knowledge; thus, some are concerned that a wide range of R&D activities might cause imperfect result because of insufficient and limited allocation of resources [63].

As aforementioned, China followed the development trajectories of South Korea in the catch-up stage. However, knowledge production strategies of China and South Korea differed in the post catch-up stage. According to the result of the knowledge strategic diagram, South Korea adopted similar knowledge production patterns in the earlier period by producing core or established knowledge. Similar patterns were shown in terms of learning strategies for developing emerging technologies as the country followed those of the catch-up paradigm [64]. On the other hand, China used relatively more keywords that were classified as emerging technologies. Despite the fact that both industrialized countries are in the process of evolving to the post catch-up paradigm, attitudes toward creating knowledge in the emerging sector were different because of different process of accumulation of technological capabilities in the catch-up process. First, the main source of intra-national knowledge flows differs. Intra-national knowledge flows are derived mainly by chaebols in South Korea, whereas intra-national knowledge flows in China are mainly derived by universities, along with some high-technology SMEs in the emerging fields [27,65]. Large entrepreneurs are relatively more likely to be locked into a well-established routine, whereas SMEs are capable of quickly learning and adapting new strategies [66]. Moreover, large entrepreneurs in South Korea have a limited contribution to the production of scientific or indigenous technological knowledge, whereas China was able to develop indigenous technological knowledge promoted by foreign direct investment (FDI) in selected technology-intensive industries [58,67]. Another reason why the Korean firms have shown a relatively passive attitude toward quantum technology is that they tend to rely on external signals that confirm the high potential of commercialization in the emerging sector [64].

The significant role of universities is in contrast to other catch-up countries in East Asia because they not only generate a highly skilled manpower base, but they also play the role of practitioner of knowledge spillover [68]. The direct involvement of the universities in the private sector, so-called *forward engineering,* is one of the distinct characteristics that China has, as the roles of universities in other catch-up countries are limited to supplying manpower to local firms [69,70]. In addition, although the initial contribution of public research institutes (PRIs) were similar to the others, the institutional reforms in 1990s forced them to actively participate in the private sector. The transformation of PRIs allowed them to be a critical driver of innovative capacities [68]. Lastly, when catching up, China had relatively higher level of science and technology than South Korea during the comparable phase (the 1960s and 1970s). This difference allowed China to skip the process of learning low level technologies and to leapfrog to the global leading stage of innovation (such as in space technology) [71].

6 | CONCLUSION

The divergence in knowledge production strategies made for emerging technologies in the late industrialized countries contrast with traditional wisdom. To demonstrate this discrepancy, this paper aimed to explore and compare how the late industrialized countries implemented knowledge production strategies for developing emerging technologies during the transition period from the catch-up to the post catch-up paradigm. Specifically, this paper developed knowledge portfolios and knowledge strategic diagrams of quantum technology for two representative late industrialized countries, South Korea and China. The results reveal that the knowledge production strategies of the two late industrialized countries are diverging, which is in contrast to the extant literature on catch-up theories.

Noteworthy findings are as follows. First, although both South Korea and China specialized in short-cycle technologies, they had different strategies for the amount of knowledge production. This implies that China is no longer considering former catch-up countries as paragons but are developing their own technological trajectories. It is assumed that the divergence has occurred because of the relationship between technology specialization and the size of the nations. Second, in terms of the knowledge strategic diagrams, South Korea tended to produce established or core knowledge, whereas China also created emerging knowledge. This implies that South Korea is still struggling to evolve to the post catch-up paradigm, whereas China is actively transforming themselves from imitators to globally leading innovators in emerging technologies. It is assumed that this is because of different levels of S&T between the two countries when they started to catch-up.

This paper provides a contribution to the literature on catch-up theories by illuminating how the knowledge production strategies of the late industrialized countries have changed after the catch-up period. Previous literature has focused on the distinct features of catch-up strategies that allowed the countries to overtake industrial leadership in the existing markets. However, in order to examine how they implemented the strategies in the transition period from catch-up to post catch-up, this paper focused on the emerging technologies, which still require several years before related markets form and thus is viable for commercialization. Accordingly, in contrast to the traditional wisdom, this paper showed that the knowledge production strategies of the late industrialized countries were diverging when they pioneered emerging technologies with high technological and market uncertainties.

This study also provides policy implications for South Korea, where R&D expenditures on emerging technologies have been increasing but impact or performance is still a struggle. First, the government needs to modify the central theme of R&D allocation. Following the RBV perspective, the country tries to allocate the R&D budget to diverse sectors that are considered emerging industries in order to detect and utilize more opportunities. However, countries with small resources should limit their scope and develop technological specializations in order to compete globally. Second, new policies need to be made to provide a more suitable environment for conducting R&D activities in emerging technologies. One of the goals of current policies that have been implemented since catch-up is suitable for creating complementary knowledge for advanced countries over a short period. Conversely, new policies are needed when producing emerging and core knowledge that would lead to world-class sophistication. Lastly, this paper also provides policy implications for other late industrializing countries to identify strategic positioning in major quantum technology fields, in reference to how other countries are developing. In the past, in-depth interviews with experts were mainly used to analyze the trend of a certain technology. However, to support evidence-based policymaking, empirical analysis of research trends is needed, and the analysis in this paper reveals which domain of knowledge is emerging and which country is specialized in which technological domain.

The limitations of this paper are as follows. First, this paper retrieved data only from WoS. WoS contains peer-reviewed papers that were published in journals with relatively high impact factors [40], implying that novel knowledge in emerging fields might not be accepted in journals from WoS because the research topics do not match. When considering that quantum technology is one of the emerging technologies, further studies are expected to include papers presented at academic conferences. Second, because this paper is an exploratory study, the result does not reveal whether which knowledge production strategies are successful. Later, when related markets are established, it would be a meaningful study to validate which features of knowledge production strategies affect the late industrialized countries' innovation performance in emerging technologies. Lastly, this paper fails to address distinctively how knowledge production strategies were implemented according to the fields of quantum technology. Thus, in future study, it will be necessary to conduct in-depth study on how the two countries manage the different post catch-up strategies of each field of technology.

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APPENDIX 1.

Search query for data collection

Classification	Subclassification	Search Query
Quantum communication	Quantum cryptography Quantum information transmission Quantum network	TS = (“quantum communication” AND (“quantum cryptography” OR (“quantum random number” OR ((single OR entangled) NEAR/1 “photon source”) OR ((free OR fiber OR space) NEAR/1 (QKD OR “quantum key distribution”)) OR ((“Si-based” OR “InGaAs/InP based” OR superconduct*) NEAR/1 (“single photon detector”)))) OR (“quantum information transmission” OR ((quantum NEAR/0 (teleport* OR “dense coding” OR memor* OR entanglement)) OR (photonic NEAR/0 (qubit OR qbit OR “quantum bit”)))) OR (“quantum network” OR (quantum NEAR/0 (repeat* OR bell OR interfac* OR (hybrid NEAR/2 system)))))
Quantum wensor/imaging	Quantum measurement Quantum sensing Quantum imaging	TS = (quantum NEAR/0 (sen* OR imag*) AND (“quantum measure” OR ((“positive operator valued measure” OR “POVM”) OR (quantum NEAR/1 tomography) OR ((entangled OR N00N OR squeezed) NEAR/0 state))) OR ((“quantum sensing” OR “quantum sensor”) OR (((photonic OR atomic OR optomechanical OR (qubit OR qbit OR “quantum bit”)) NEAR/1 sens*))) OR ((“quantum image” OR “quantum imaging”) OR (“ghost imaging” OR “quantum lithography” OR “quantum illumination” OR “quantum ellipsometry”)))
Quantum computing	Quantum simulator Physical quantum bits Logical quantum bits Quantum software	TS = ((“quantum computing” OR “quantum computer”) AND ((“quantum simulator” OR “quantum simulation”) OR (“quantum annealer” OR (“ultra cold” NEAR/5 (“trapped ion” OR “quantum gas”)) OR (“quantum dot” NEAR/0 array) OR (“semiconductor nanostructure” NEAR/2 polariton) OR (“josephson junction” AND (superconduct* NEAR/0 (qubit OR qbit OR “quantum bit”))) OR “photonic platform”)) OR ((“physical quantum bit” OR “physical qubit” OR “physical qbit”) OR ((superconduct* OR quantum) NEAR/1 circuit*) OR (semiconductor NEAR/0 (qubit OR qbit OR “quantum bit”))) OR ((“logical quantum bit” OR “logical qubit” OR “logical qbit”) OR (“quantum error correction” OR “decoherence control” OR “quantum characterization”)) OR (“quantum software” OR (quantum NEAR/0 (algorithm OR compiler OR “system software” OR “machine learning” OR “computer architecture” OR “computing theory” OR “computation model”))))