



# Technological Trajectory Analysis of Patent Citation Networks: Examining the Technological Evolution of Computer Graphic Processing Systems

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## Abstract

This paper quantitatively analyzes how technology has evolved within the technological field of computer graphic processing systems. A path-dependent technological development path is called a ‘technological trajectory’ in the field of Innovation Economics. The technological trajectory of a technological field can be mapped as the main paths of patent citation networks. Using a method called main path analysis, main paths are calculated from the whole patent citation network data of the technological field. This paper examines how technology has evolved within the technological field of computer graphic processing systems using main path analysis. In addition, the change of the main paths over time is analyzed. According to this analysis, the appearances and disappearances of nodes on the main paths show certain patterns. First, all nodes observed on the main paths three times consecutively at 5-year intervals did not drop out from the main paths in the long term. Second, most of the appearances and disappearances of the nodes occur toward the end of the main paths. These observations are consistent with the technological lock-in process. The result of this research suggests that it takes less than 10 years to determine which technologies are locked-in. In addition, various patterns of the appearances and disappearances of companies owning patents on the main paths are also observed. Three companies are taken as examples to illustrate these patterns. These observations provide insight into how knowledge networks are formed.

**Keywords** Technological trajectory · Technological evolution · Patent · Main path analysis

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## 1 Introduction

This paper quantitatively analyzes how technology has evolved within the technological field of computer graphic processing systems. Although digital technology is rapidly evolving and becoming increasingly incorporated into daily life, the understanding of the technological evolution process is still incomplete. To improve this understanding, this paper aims to contribute to the elucidation of the mechanism of the technological evolution process in a quantitative way.

The idea of a technological trajectory and a method called main path analysis are used in this paper. The evolution of technology starts with an initial breakthrough. This fundamental breakthrough sets the direction of incremental improvements. At the same time, technology is diffused during these improvements. Hence, the evolution of technology is a cumulative process. Dosi [1] described this combined process, which contains fundamental breakthroughs, incremental improvements, and diffusion, using two notions, “technological paradigm” and “technological trajectory”. In a technological field, development paths are dependent on the technological paradigm. The technological paradigm is selected in the initial stage of the technological field and technological development must proceed according to the technological paradigm. The direction of technological development is limited by the selection of the technological paradigm. While there are many possible directions of technological development, only a small fraction of these directions are realized. Thus, Dosi [1] described the development paths of technology qualitatively.

Verspagen [2] developed this research in a quantitative way. Verspagen [2] applied a network analysis algorithm called main path analysis to the patent citation network of the technological field of fuel cells. Patent data have been used as an indicator of technology for a long time. In particular, patent citation network data have been regarded as a network which maps ideas and their relatedness. Each patent can be considered as a piece of knowledge. Also, citations to a previous patent mean that the knowledge written in the following patents improves the knowledge described in the previous patent in some way. According to this idea, patent citation network data can be considered a map of the incremental evolution of knowledge. The idea of a technological trajectory suggests that the whole patent citation network data of a technological field contains the main flow of knowledge.

The technological field of computer graphic processing systems is chosen as the target of this research. The importance of this technological field is growing together with the evolution of artificial intelligence (AI). Image recognition is an important technological field of AI. Additionally, many manufacturers use computer-aided design (CAD) software to design products. GPUs are necessary to use CAD software on PCs. The technological evolution of the technological field of computer graphic processing systems has great significance for the productivity of the manufacturing industry. Thus, examining the technological evolution of computer graphic processing systems is particularly significant now.

The patent data in this paper are gathered from USPTO PatentsView. The number of patents that were published within the technological field of computer graphic processing systems is 4032. Patent citation network data with this number of patents are not easy to summarize from the viewpoint of technological evolution. However, an algorithm called main path analysis enables us to summarize the whole network [2]. Main path analysis is a method to analyze a directed network by connectivity analysis. This method was proposed by Hummon and Doreian [3]. Main path analysis is frequently used to explore citation networks. In this paper, the technological trajectory from the whole patent citation network data of computer graphic processing systems is mapped using main path analysis. Following Verspagen [2], this paper examines the main paths as analyzed from the viewpoint of selectivity. Furthermore, the change of the main paths is analyzed over time. These observations provide insight into how knowledge networks are formed.

This paper consists of six sections. After the introduction, a literature review follows. In the literature review, previous studies that are related to the idea of technological trajectories and main path analysis are reviewed. In Sect. 3, a brief history of the technological field of graphic processing systems is presented. In Sect. 4, the main paths of the period from 1975 to 2015 are examined. In Sect. 5, the change of the main paths over time is analyzed. Concluding remarks follow in Sect. 6.

## 2 Review of Previous Studies

In this section, three categories of previous studies are reviewed. First, previous studies related to the idea of technological trajectories are reviewed. Second, a review of previous studies using main path analysis follows. Finally, previous studies related to the technological lock-in process are reviewed.

As mentioned in Sect. 1, the idea of a technological trajectory was presented by Dosi [1]. Technological trajectories consist of cumulative and path-dependent development paths within a technological field. The idea of technological trajectories has often been used in the research field of technological evolution. Since Dosi [1], researchers have mainly used qualitative methods to study technological evolution and technological trajectories [4, 5]. Thus, in the research field of technological trajectories, qualitative research has been mainly cumulative. On the other hand, Verspagen [2] advanced the research field by proposing a quantitative method to find technological trajectories within a citation network data set. Verspagen [2] employed a method called main path analysis proposed by Hummon and Doreian [3]. Main path analysis is a method to map the major flow of knowledge within a field as citation networks. There are two steps to this method. First, every edge in the whole citation network of a field is weighed by connectivity. This weight is called traversal weight. This count represents the significance of an edge. Second, based on traversal weight, the main paths are searched by an algorithm which chains important edges in the citation network. The procedure of main path analysis will be explained in detail in Sect. 4. Hummon and Doreian [3] developed this method to find the main knowledge flow within the research field of DNA studies. Verspagen [2] argued that the method of main path analysis could be applied to find technological trajectories

within a patent citation network. The main paths, which represent the major flow of knowledge within a technological field, can be considered as technological trajectories mapped as citation networks. Verspagen [2] applied main path analysis to find technological trajectories within the technological field of fuel cells. After Verspagen [2], some studies employed main path analysis to find technological trajectories within the technological fields of data communication [6] and telecom switching [7]. Also, Barberá-Tomás et al. [8] confirmed the validity of main path analysis as a method for studying technological evolution. In addition to these studies, Huenteler et al. [9] applied the main paths of patent citation networks calculated by the method of Hummon and Doreian [3] to study the difference between technological life-cycles of solar PV and wind power. Huenteler et al. [9] compared the features of the main paths to models of technological life-cycles presented by Abernathy and Utterback [10] and Davies and Hobday [11]. Main path analysis is also used to study knowledge evolution in various academic research fields. In these studies, academic paper citation network data are examined using main path analysis. For example, Yu and Sheng [12] used main path analysis to study knowledge evolution in the research field of blockchain technology. Other studies examined the knowledge evolution of the research field of data quality, environmental innovation, IT outsourcing, text mining, data envelopment analysis, new energy vehicles, lithium iron phosphate batteries and the Internet of Things [13–20].

Thus, main path analysis has been commonly used as a method to study technological and knowledge evolution. However, the method of Hummon and Doreian [3] fails to include the edges which have large traversal counts in some cases. Liu and Lu [21] proposed a method called key-route search to solve this problem. Key-route search is the newest method to find main paths implemented in the network analysis software Pajek, which was used to conduct main path analysis in this research. de Nooy et al. [22] explained in detail the procedure for analysing main paths in Pajek. After Liu and Lu [21], additional new approaches to main path analysis have been proposed. For example, Liu and Kuan [23] proposed a new approach to main path analysis taking into account knowledge decay.

In Sect. 5, the change of main paths will be analyzed. Through the evolution of main paths, some paths appear and some paths disappear. These appearances and disappearances can be considered as entries and exits of technology into the mainstream of a technological field. Also, some nodes never disappear from the main paths. This pattern can be considered lock-in of technology in a technological field. This technological change has been discussed in the research field of evolutionary economics. Especially, Nelson and Winter [24] brought the idea of evolution into the research field of economics. They focus on the approximation of competition with economic actors in the market and the competition of genes in nature. Technological change was discussed in Nelson and Winter [24] from the viewpoint of evolutionary economics. Arthur [25] modelled the mechanism of the lock-in process of technology in the case of two competing technologies with increasing returns. Also, some case studies of technological lock-in have been done in the research field of innovation economics. David [26] studied the lock-in process of keyboard layouts. There are also other case studies about lock-ins in other technological standards such as the DVD [27] and mobile telecommunication [28].

### 3 A Brief History of Computer Graphic Processing Systems

In this section, the history of computer graphic processing systems is reviewed. This review is largely based on McClanahan [29] and Singer [30]. The technological field of computer graphic processing systems has advanced together with the evolution of the graphics processing unit (GPU). In 1999, NVIDIA introduced the term “GPU”. Until this time, the term “GPU” did not exist. However, this term will be used throughout this section to ensure consistency. GPUs are designed for 3D graphics rendering calculations. The original GPU designs were based on the graphics pipeline concept. The graphics pipeline is a conceptual model that consists of several stages. Through the stages, 3D space is converted to 2D pixel space on the screen. In the early GPU hardware, only the rendering stage of the graphics pipeline was implemented. The graphics pipeline stages which are implemented in GPU hardware increased as GPU technology advanced. In 1999, the first GPUs, which implemented the whole graphics pipeline (transform, lighting, triangle setup and clipping, rendering) in their hardware were released. GeForce 256 of NVIDIA and Radeon 7500 of ATI are examples of these first true GPUs. The first graphics pipeline completely implemented in GPU hardware was called a “fixed function” pipeline because the data which was sent to the pipeline could not be modified. In 2001, NVIDIA released Geforce 3 which implemented the programmable pipeline. Using the programmable pipeline, the data can be operated while in the pipeline. The programmability of GPUs began to progress from 2001. Other examples of GPUs at this time are ATI Radeon 8500 and the X-Box of Microsoft. In 2010, NVIDIA released a GPU architecture called Fermi Architecture. This architecture was designed for general-purpose computing on graphics processing units (GPGPU), which allowed programmers to use GPU resources not only for graphics processing. Thus, the GPU hardware has advanced from a single core, fixed-function hardware pipeline implementation just for graphics to a set of programmable cores for general computing purposes [29].

### 4 Main Path Analysis

In this section, the patent citation network dataset of the technological field of computer graphic processing systems is analyzed using the methodology of Verspagen [2] and Liu and Lu [21].

#### 4.1 Data and Methodology

In this section, the data and the methodology which are used for the analysis are introduced. The US Patent Office database is used to obtain the entire patent citation network data in the technological field of computer graphic processing systems. This field is defined by the technological classes of US Patent Classification (USPC) under Class 345/501 (inclusive). There are eight subclasses (345/502, 345/503,

345/504, 345/505, 345/506, 345/519, 345/520, 345/522) under this class. Class 345/501 is for the technological field of the “Computer graphic processing system”. According to the class definition, patents of “subject matter comprising apparatus or a method for processing or manipulating data for presentation by a computer prior to use with or in a specific display system” (USPC class numbers and titles, Class 345/501) are classified under Class 345/501. There are many more patents that are essential for the evolution of computer graphic processing systems. For example, patents which are classified as Class 382 are about image analysis, which is a subject that is strongly related to computer graphic processing systems. However, in this research, the patents which are not included in the classes under Class 345/501 are not examined to keep the data manageable. Also, the citations that are examined in this research are citations within the classes under Class 345/501. The US Patent Office online database called PatentsView covers the patents which are published from 1975 to 2015. The history of computer graphic processing systems started in the 1970s, so the scope of the database is adequate for this research. The number of patents that are available on PatentsView in the classes under Class 345/501 (Inclusive) is 4032. After collecting all patents, a citation network data set of the technological field of computer graphic processing systems is created. Python and its network analysis package NetworkX are used to create this citation network data set. In the citation network data set, every node represents a patent, and every directed edge represents a citation. The citation network data set in this research contains 4032 nodes and 13,147 edges. Every edge is directed to a citing patent from a cited patent according to the flow of knowledge. For example, in Fig. 2, an edge is directed to node C from node A. This edge represents a relationship in which patent C cites patent A. Patent citation networks are always directed acyclic graphs (DAGs) because no patents cite patents that are newer than them. Also, some patents are never cited but cite others. Such patents become sink nodes in the network. Sink nodes are called “endpoints” in this research. At the same time, some patents are cited but cite nothing in the citation network. Such patents become source nodes of the network. Source nodes are called “startpoints” in this research. Figure 1 provides the basic statistics of the citation network data set.

Main path analysis is used to identify the main flow of knowledge within the technological field. As mentioned in Sect. 2, the main path analysis method was invented by Hummon and Doreian [3]. They invented this method to find the main flow of knowledge within the research field of DNA theory. Later Verspagen [2] applied this method to identify technological trajectories within the technological field of fuel cell research.

In the main path analysis method, every edge in the citation network data is first weighted according to its position in the network. The weight of edges is called the “traversal count”. The search path count method is used to weigh every edge in an acyclic network. The term “search path” means a route that connects a pair of nodes in the network. Every search path is a sequence of directed edges. For example, in Fig. 2, a search path A-C-D-F connects the node A to the node F. There are two search path count methods, search path link count (SPLC) and search path node pair (SPNP). Search path link count (SPLC) is a method proposed by Hummon and Doreian [3]. In this method, every edge is weighed by counting how often

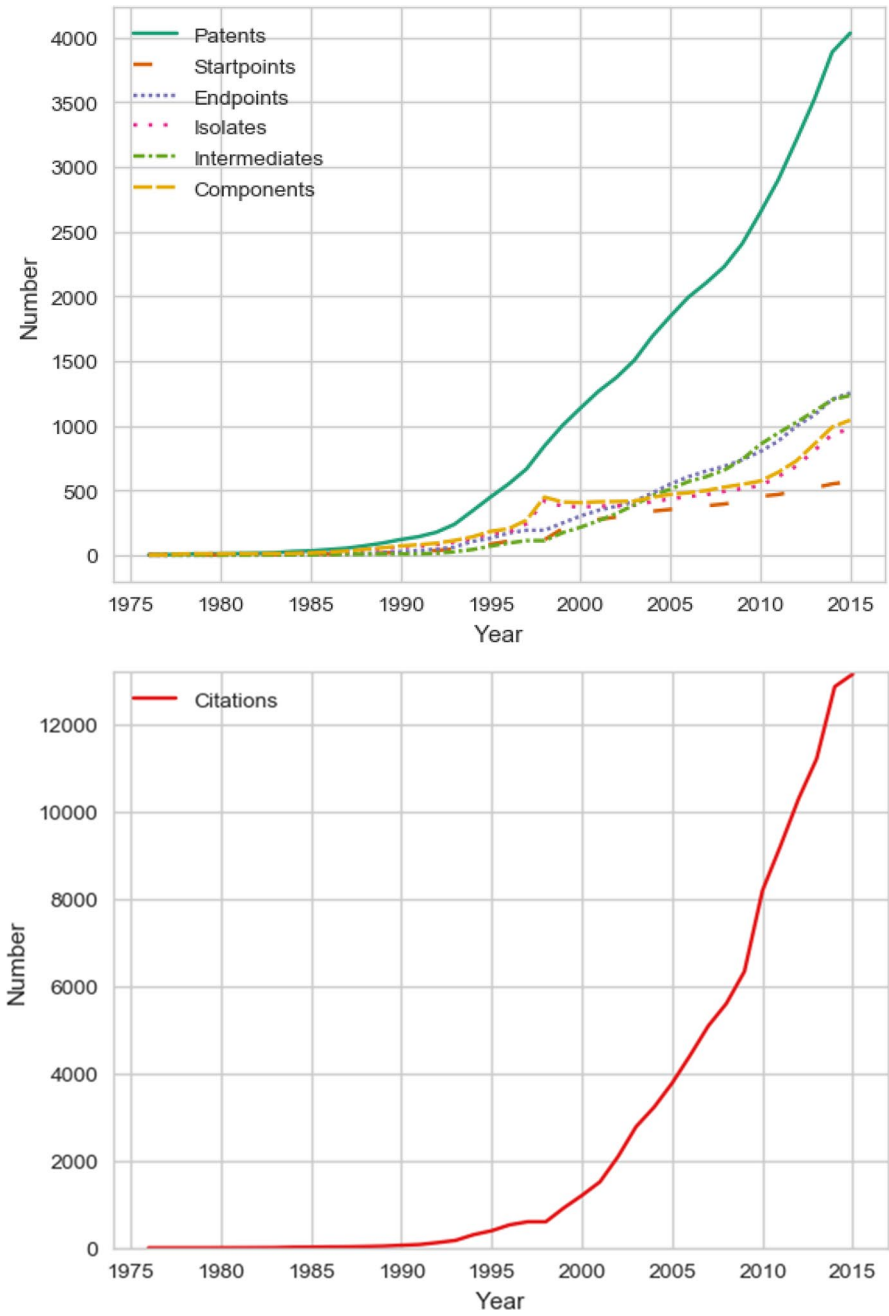
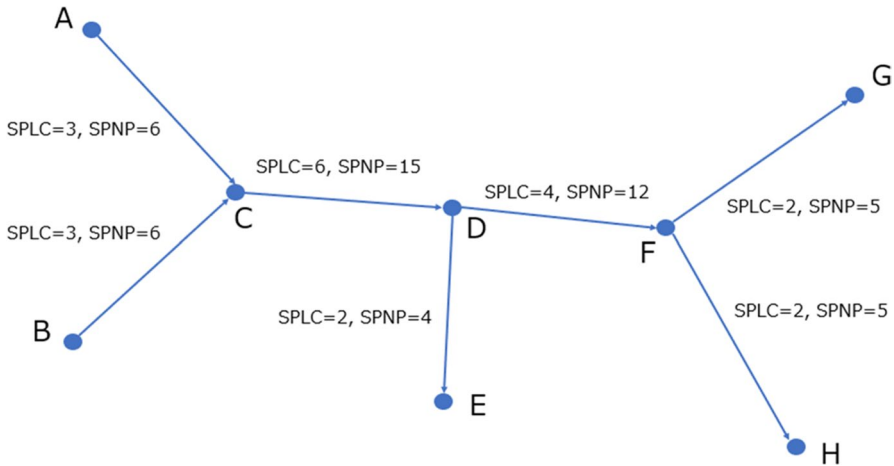


Fig. 1 Trend of the whole citation network



**Fig. 2** Calculating SPLC and SPNP values

the edge lies on all possible search paths. Hummon and Doreian [3] imply that the SPLC method contains search paths whose origins are intermediate nodes or search paths whose destinations are intermediate nodes. However, the method can also be considered to contain only search paths whose origins are startpoints and whose destinations are also endpoints. In this research, the SPLC method is considered to contain only search paths whose origins are startpoints and destinations are also endpoints. Hummon and Doreian [3] also proposed another method to weigh edges. This method is called the search path node pair (SPNP). The edge D-F connects four nodes (A, B, C, D) to its destination, for example, the node G. At the same time, the edge D-F connects three nodes (F, G, H) to its origin, for example, the node A. The SPNP value of the edge D-F is calculated by multiplying these numbers. Thus, the SPNP value of the edge D-F is  $3 \times 4 = 12$ . This number represents how many pairs of nodes the edge D-F connects. Both SPLC and SPNP weigh nodes which are more responsible for connecting other nodes. As Verspagen [2] and Fontana et al. [6] mentioned, the result is not very different between these two methods. In this research, the SPNP method is used following Verspagen [2] and Fontana et al. [6]. After finishing weighing edges, the following algorithm proposed by Hummon and Doreian [3] is adopted to define main paths within a network. The algorithm below is created in reference to Verspagen [2].

- (i) For each startpoint in the network, pick the outward edge that has maximum SPNP value among all edges going outward of the startpoint. If some edges have the same maximum SPNP value, take all these edges.
- (ii) Select the startpoint(s) which are selected in Step (i). This is the startpoint(s) of the main paths.
- (iii) Take the target(s) (citing patent) of the edge(s) identified in the previous step.
- (iv) From the target(s) identified in the previous step, pick (again) the outward edge that has the maximum SPNP value among all outward edges from this node

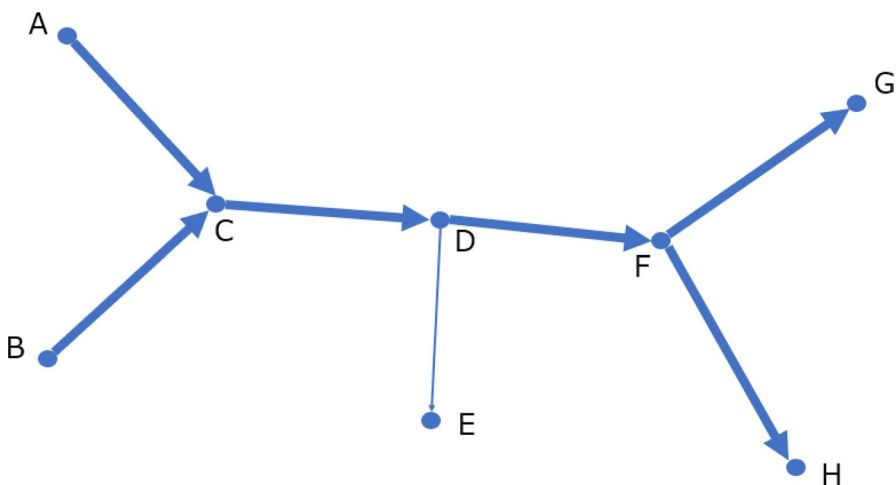


and add this edge to the main paths. If some edges have the same maximum SPNP value, add all these edges to the main paths. If (all) these edge(s) point to an endpoint of the network, exit the algorithm, otherwise go back to Step (iii) and continue.

The main paths which can be found by this algorithm are called the local main paths. This algorithm suffers from the limitation that sometimes it does not include the edges which have large traversal counts. To avoid this problem, Liu and Lu [21] invented a new method called key-route search. Key-route search guarantees that the local key-route main paths, which are calculated by the method, contain edges with the highest traversal counts. According to Liu and Lu [21], the key-route search procedure is as follows. The algorithm below is created in reference to Liu and Lu [21].

- (i) Select the key-route, which is the links that have the highest traversal count.
- (ii) Search forward from the end node of the key-route until a sink is hit.
- (iii) Search backward from the start node of the key-route until a source is hit.

“Search forward” is the same as steps (iii) and (iv) of Hummon and Doreian’s method [3] presented previously. “Search backward” represents searching the roots of the edges using steps (iii) and (iv) of Hummon and Doreian [3]. The local key-route main paths are calculated by this procedure. The local key-route main paths within the network of Fig. 2 are presented by thick lines in Fig. 3. The authors use the key-route search method to find the main paths in the whole citation network data. A network analysis software called Pajek is used to conduct main path analysis.



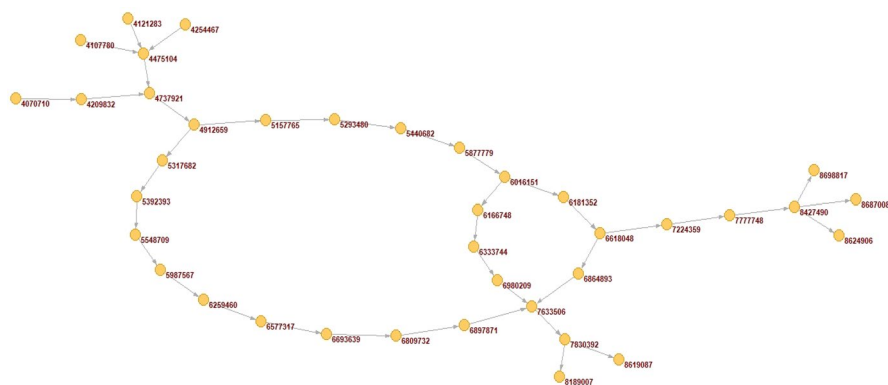
**Fig. 3** The local key-route main paths of the network presented in Fig. 2

## 4.2 Result

The main paths of the technological field of computer graphic processing systems are calculated using the method presented in Sect. 4.1. In the calculation, the patents which do not cite and are not cited are excluded because they are isolated and out of the flow of knowledge. Figure 4 presents the main paths calculated. Table 1 presents information about each patent presented in Fig. 4.

In Fig. 4 and Table 1, some technological convergences, where paths converge at a node, and some technological divergences, which represent where a path diverges into multiple paths at a node, are observed. First, on the upper-left side of Fig. 4, seven patents converge to Patent 4912659. This patent is about a parallel surface processing system for graphics display. These seven patents which converged are mainly targeted at professional fields like the medical industry (4070710, 4121283, 4737921) and the military industry (4209832). Two paths start from Patent 4912659. The path which goes down is directed linearly to Patent 7633506. There are nine patents between Patent 4737921 and Patent 7633506 on this path. The other path is directed to Patent 6016151. This flow is split into two. One path is directed to Patent 7633506. The other path is split into two again, and one is directed to Patent 7633506. Thus, three flows of technological development converge at Patent 7633506. At this point, twenty-eight patents out of thirty-nine patents on the main paths converge. Patent 7633506 is about a parallel pipeline graphics system, which advanced the technological field of GPU from single pipeline implementation to  $2^n$  parallel pipeline implementation. Three patents are on the paths from Patent 7633506. Several paths also begin from Patent 6618048.

Verspagen [2] also mentioned that there is selectivity in the main paths in the sense that many nodes converge to a small number of endpoints. He compares the fraction of endpoints in the whole citation network data and the fraction of endpoints on the main paths to check the existence of this selectivity. In the research case of Verspagen [2], 21.4% of the nodes are endpoints in the whole citation network, and 5.0% of the nodes are endpoints on the main paths. The fraction of endpoints is



**Fig. 4** The main paths for the technological field of computer graphic processing systems, 1975–2015

**Table 1.** Patents presented in Fig. 4

Pat No.	Year	Assignee	Patent content
4070710	1978	NuGraphics, Inc	Raster scan display apparatus for dynamically viewing image elements stored in a random access memory array
4107780	1978	National Research Development Corporation	Display apparatus
4121283	1978	Cromemco Inc	Interface device for encoding a digital image for a CRT display
4209832	1980	Chrysler Corporation	Computer-generated display for a fire control combat simulator
4254467	1981	Xerox Corporation	Vector to raster processor
4475104	1984	Lexidata Corporation	Three-dimensional display system
4737921	1988	Dynamic Digital Displays, Inc	Three dimensional medical image display system
4912659	1990	International Business Machines Corporation	Parallel surface processing system for graphics display
5157765	1992	International Business Machines Corporation	Method and apparatus for pipelined parallel rasterization
5293480	1994	AT&T Bell Laboratories	High resolution graphics system architecture
5317682	1994	International Business Machines Corporation	Parametric curve evaluation method and apparatus for a computer graphics display system
5392393	1995	Sun Microsystems, Inc	Architecture for a high performance three dimensional graphics accelerator
5440682	1995	Sun Microsystems, Inc	Draw processor for a high performance three dimensional graphic accelerator
5548709	1996	Silicon Graphics, Inc	Apparatus and method for integrating texture memory and interpolation logic in a computer system
5877779	1999	Sun Microsystems, Inc	Method and apparatus for efficient rendering of three-dimensional scenes
5987567	1999	Apple Computer, Inc	System and method for caching texture map information
6016151	2000	NeoMagic Corp	3D triangle rendering by texture hardware and color software using simultaneous triangle-walking and interpolation for parallel operation
6166748	2000	Silicon Graphics, Inc	Interface for a high performance low cost video game system with coprocessor providing high speed efficient 3D graphics and digital audio signal processing
6181352	2001	Nintendo Co., Ltd	Graphics pipeline selectively providing multiple pixels or multiple textures
6259460	2001	NVIDIA Corporation	Method for efficient handling of texture cache misses by recirculation
6333744	2001	Silicon Graphics, Inc	Graphics pipeline including combiner stages
6577317	2003	NVIDIA Corporation	Apparatus and method for geometry operations in a 3D-graphics pipeline
		Apple Computer, Inc	

Table 1. (continued)

Pat No.	Year	Assignee	Patent content
6618048	2003	Nintendo Co., Ltd	3D graphics rendering system for performing Z value clamping in near-Z range to maximize scene resolution of visually important Z components
6693639	2004	Apple Computer, Inc	Graphics processor with pipeline state storage and retrieval
6809732	2004	NVIDIA Corporation	Method and apparatus for generation of programmable shader configuration information from state-based control information and program instructions
6864893	2005	NVIDIA Corporation	Method and apparatus for modifying depth values using pixel programs
6897871	2005	ATI Technologies, Inc	Graphics processing architecture employing a unified shader
6980209	2005	NVIDIA Corporation	Method and system for scalable, dataflow-based, programmable processing of graphics data
7224359	2007	NVIDIA Corporation	Depth clamping system and method in a hardware graphics pipeline
7633506	2009	ATI Technologies ULC	Parallel pipeline graphics system
7777748	2010	Lucid Information Technology, Ltd	PC-level computing system with a multi-mode parallel graphics rendering subsystem employing an automatic mode controller, responsive to performance data collected during the run-time of graphics applications
7830392	2010	NVIDIA Corporation	Connecting multiple pixel shaders to a frame buffer without a crossbar
8189007	2012	Samsung Electronics Co., Ltd	Graphics engine and method of distributing pixel data
8427490	2013	NVIDIA Corporation	Validating a graphics pipeline using pre-determined schedules
8619087	2013	NVIDIA Corporation	Inter-shader attribute buffer optimization
8624906	2014	NVIDIA Corporation	Method and system for non stalling pipeline instruction fetching from memory
8687008	2014	NVIDIA Corporation	Latency tolerant system for executing video processing operations
8698817	2014	NVIDIA Corporation	Video processor having scalar and vector components

**Table 2** Top patent-holding organizations in the whole citation network

	Organization	Patents	Fraction
1	NVIDIA Corporation	384	0.125696
2	International Business Machines Corporation	158	0.051718
3	Microsoft Corporation	157	0.051391
4	Intel Corporation	147	0.048118
5	Hewlett-Packard Development Company, L.P	114	0.037316
6	Sun Microsystems, Inc	89	0.029133
7	Apple Inc	80	0.026187
8	Hitachi, Ltd	70	0.022913
9	Canon Kabushiki Kaisha	50	0.016367
10	Silicon Graphics, Inc	47	0.015385

**Table 3** Top patent-holding organizations on the main paths

	Organization	Patents	Fraction (main paths)	Fraction (All)
1	NVIDIA Corporation	12	0.315789	0.125696
2	Sun Microsystems, Inc	3	0.078947	0.029133
2	Apple Computer, Inc	3	0.078947	0.010802
2	International Business Machines Corporation	3	0.078947	0.051718
2	Silicon Graphics, Inc	3	0.078947	0.015385
6	Nintendo Co., Ltd	2	0.052632	0.010802

smaller on the main paths than in the whole citation network. Based on this observation, Verspagen [2] mentioned that there is selectivity in the main paths because the level of convergence is higher in the main paths than the whole network. In our research, 16.4% of the nodes are endpoints on the whole citation network, and 13.0% of the nodes are endpoints on the main paths. The fraction of endpoints is larger in the main paths than in the whole citation network. However, the difference between these fractions is not as great as in Verspagen [2]. Based on this observation, the authors conclude that there is selectivity in the sense that many nodes converge to a small number of endpoints, but the selectivity is not as strong as in the research case of the technological field of the fuel cell examined by Verspagen [2].

Table 2 presents the top ten organizations that hold large numbers of patents. The top five organizations in this table together hold 30% of the patents in the aggregate citation network data. NVIDIA Corporation, which is ranked the top organization in the table, is the leading company in the GPU industry now.

Table 3 shows the companies that have multiple patents on the main paths. In this table, the fraction of patents that the companies have on the main paths and the fraction of patents the companies have in the whole citation network are compared. The fraction of patents the companies have on the main paths is larger than the fraction of patents the companies have in the whole citation network. As in Table 2, the organization that is ranked at the top of the table is NVIDIA Corporation, which is the current

leading company in the technological field. On the other hand, the other companies in Table 3 are ranked differently from Table 2. For example, some companies that appear in Table 2 do not appear in Table 3. Microsoft Corporation is ranked number 3 in Table 2, but does not appear in Table 3. As seen in Table 3, Microsoft Corporation does not have any patents on the main paths. On the contrary, Nintendo Co., Ltd. appears in Table 3, even though Nintendo Co., Ltd. is not ranked in Table 2. Therefore, it can be said that the set of companies that hold patents on the main paths is different from the set of companies that hold a large number of patents in the whole network. This difference suggests that selectivity exists in the main paths at the firm level.

Table 1 shows a trend in the appearance of organizations in the main paths. For example, from 1990 to 1994, International Business Machines Corporation owned three patents out of the four patents in this period. From 1995 to 1999, Sun Microsystems, Inc. owned three patents out of the four patents. Neither International Business Machines Corporation nor Sun Microsystems, Inc. owned any patent on the main paths outside these periods. From 2001 to 2014, twelve patents out of twenty patents were owned by NVIDIA Corporation, which did not appear on the main paths before 2001. This trend suggests that the most critical role of technological development was played by a single organization and the organization which plays this role changes over time.

## 5 The Change of Main Paths Over Time

In Sect. 4, the patent citation network dataset of the technological field of computer graphic processing systems was analyzed using the methodology of Verspagen [2]. In this section, main path analysis is repeated on patent citation network datasets of different periods. Using this method, “snapshots” of the main paths over time can be produced. These “snapshots” of main paths are compared to produce assumptions for a better understanding of the mechanism of technological evolution.

### 5.1 Data and Methodology

In this section, the data and the methodology used for the analysis are introduced. The same dataset is used as in the analysis in Sect. 4. Main path analysis, which is introduced in Sect. 4.1, is also used. In this section, main path analysis is repeated for a sequence of periods to obtain a series of “snapshots” of main paths every 5 years. The sequence of periods is as follows: from 1975 to 1985, from 1975 to 1990, from 1975 to 1995, from 1975 to 2000, from 1975 to 2005, from 1975 to 2010, from 1975 to 2015. Using this methodology, main paths in the year 1985, 1990, 1995, 2000, 2005, 2010, and 2015 can be obtained.

### 5.2 Result

The main paths of the technological field of computer graphic processing systems are calculated using the method presented in Sects. 4.1 and 5.1. Figures 5, 6, 7, 8, 9, 10 and 11 shows the seven main paths calculated. Table 4 shows which patents

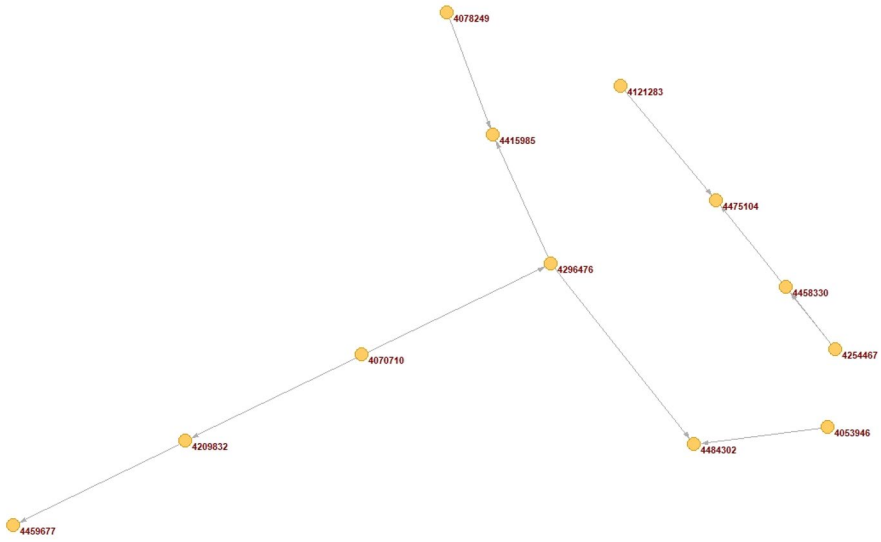


Fig. 5 The main paths of the technological field of computer graphic processing systems 1975–1985

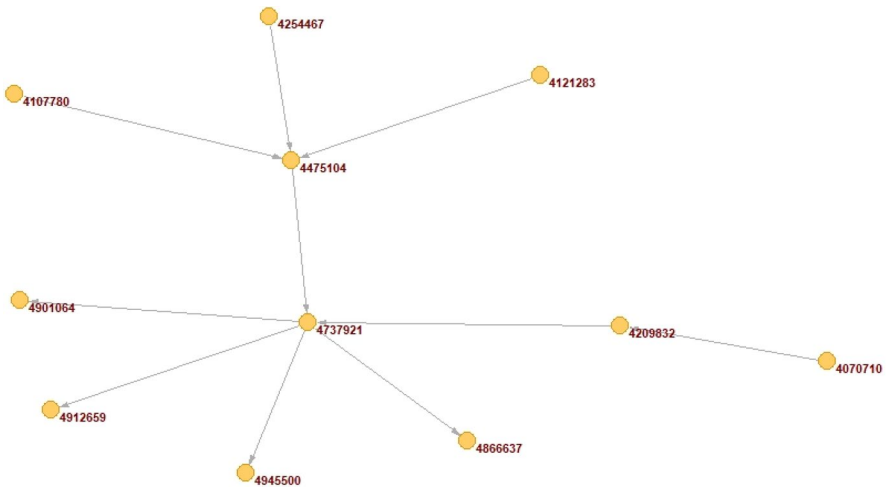
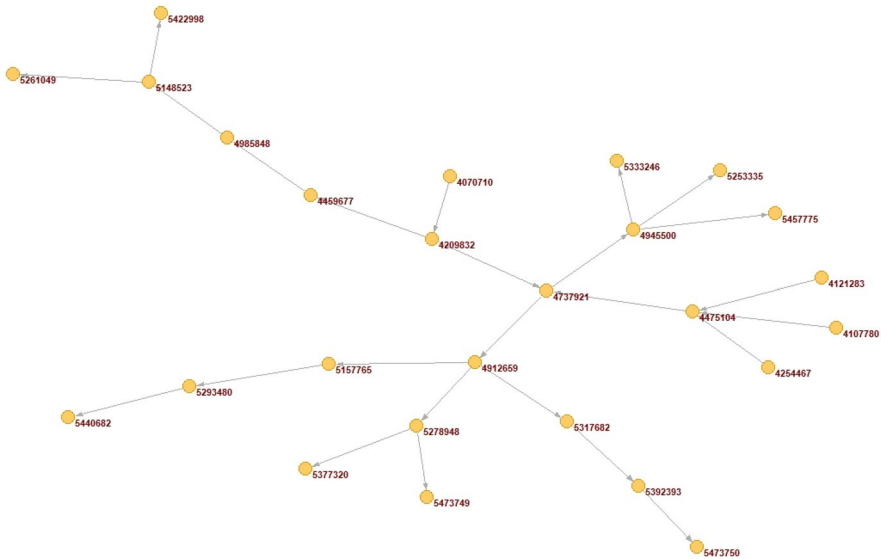


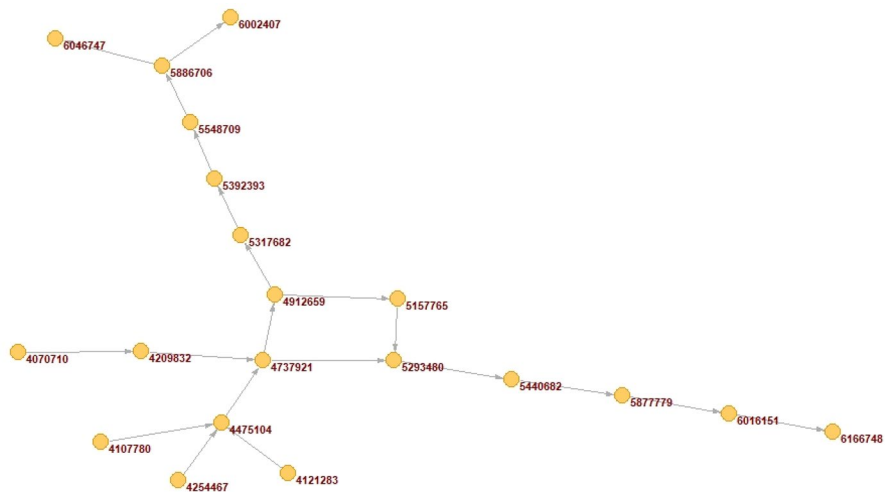
Fig. 6 The main paths of the technological field of computer graphic processing systems 1975–1990

are included in which main paths. In this table, a “✓” indicates that the patent was on the main paths in the year of that column. Based on this table, patterns of nodes’ appearances and disappearances on the main paths are examined.

From Figs. 5, 6, 7, 8, 9, 10 and 11 and Table 4, some patterns of nodes’ appearances and disappearances on main paths can be derived. First, all nodes that are observed on the main paths three times consecutively at five-year intervals did not



**Fig. 7** The main paths of the technological field of computer graphic processing systems 1975–1995



**Fig. 8** The main paths of the technological field of computer graphic processing systems 1975–2000

drop out from the main paths in the long term. In every row in Table 4, when a “✓” appears three times consecutively, it will keep appearing in the remainder of the row. Second, most of the appearances and disappearances of the nodes occur toward the end of the main paths. These observations are consistent with the theory of a technological lock-in process. Nodes toward the end of the main paths can be considered as competing technologies that are not yet locked in. The nodes that are locked into



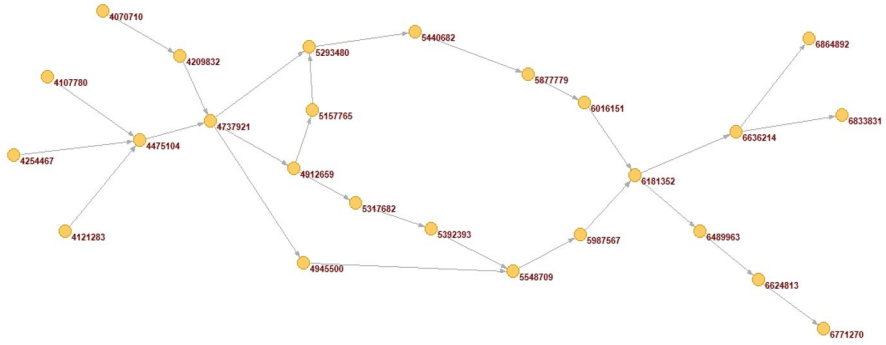


Fig. 9 The main paths of the technological field of computer graphic processing systems 1975–2005

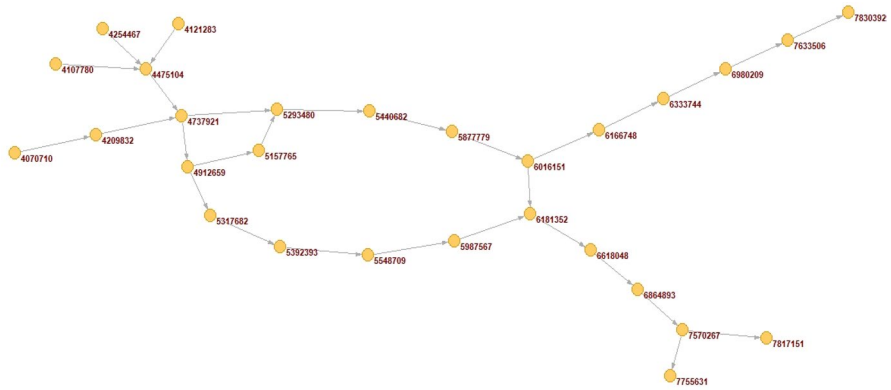


Fig. 10 The main paths of the technological field of computer graphic processing systems 1975–2010

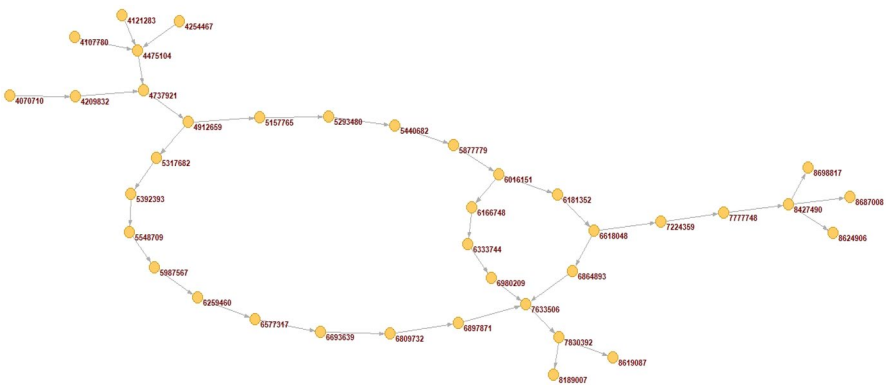


Fig. 11 The main paths of the technological field of computer graphic processing systems 1975–2015

**Table 4** Patents presented in Figs. 5, 6, 7, 8, 9, 10 and 11

Patent No.	Date	Organization	~1985	~1990	~1995	~2000	~2005	~2010	~2015
4053946	1977/10/11	Hughes Aircraft Company	✓						
4070710	1978/1/24	NuGraphics, Inc	✓	✓		✓	✓	✓	✓
4078249	1978/3/7	Raytheon Company	✓						
4107780	1978/8/15	National Research Development Corporation		✓	✓	✓	✓	✓	✓
4121283	1978/10/17	Cromenco Inc	✓	✓	✓	✓	✓	✓	✓
4209832	1980/6/24	Chrysler Corporation	✓	✓	✓	✓	✓	✓	✓
4254467	1981/3/3	Xerox Corporation	✓	✓	✓	✓	✓	✓	✓
4296476	1981/10/20	Atari, Inc	✓						
4415985	1983/11/15	The Bendix Corporation	✓						
4458330	1984/7/3	Intergraph Corporation	✓						
4459677	1984/7/10	Ampex Corporation	✓	✓					
4475104	1984/10/2	Lexidata Corporation	✓	✓		✓	✓	✓	✓
4484302	1984/11/20	International Business Machines Corporation	✓						
4737921	1988/4/12	Dynamic Digital Displays, Inc		✓	✓	✓	✓	✓	✓
4866637	1989/9/12	International Business Machines Corporation		✓					
4901064	1990/2/13	Schlumberger Technology Corporation		✓					
4912659	1990/3/27	International Business Machines Corporation		✓	✓	✓	✓	✓	✓
4945500	1990/7/31	Schlumberger Technology Corporation		✓	✓		✓		
4985848	1991/1/15	Visual Information Technologies, Inc		✓	✓				
5148523	1992/9/15	Solbourne Computer, Inc		✓	✓				
5157765	1992/10/20	International Business Machines Corporation		✓	✓	✓	✓	✓	✓
5253335	1993/10/12	Matsushita Electric Industrial Co., Ltd		✓	✓				
5261049	1993/11/9	International Business Machines Corporation		✓	✓				
5278948	1994/1/11	International Business Machines Corporation		✓	✓				

**Table 4** (continued)

Patent No.	Date	Organization	~1985	~1990	~1995	~2000	~2005	~2010	~2015
5293480	1994/3/8	AT&T Bell Laboratories		✓		✓	✓	✓	✓
5317682	1994/5/31	International Business Machines Corporation		✓		✓	✓	✓	✓
5333246	1994/7/26	Seiko Epson Corporation		✓					
5377320	1994/12/27	Sun Microsystems, Inc		✓		✓	✓	✓	✓
5392393	1995/2/21	Sun Microsystems, Inc		✓		✓	✓	✓	✓
5422998	1995/6/6	<i>Not assigned to any organization</i>		✓					
5440682	1995/8/8	Sun Microsystems, Inc		✓		✓	✓	✓	✓
5457775	1995/10/10	International Business Machines Corporation		✓					
5473749	1995/12/5	Sony Corporation		✓					
5473750	1995/12/5	Fujitsu Limited		✓					
5548709	1996/8/20	Silicon Graphics, Inc				✓	✓	✓	✓
5877779	1999/3/2	Sun Microsystems, Inc				✓	✓	✓	✓
5886706	1999/3/23	Hewlett-Packard Development Company, L.P				✓	✓	✓	✓
5987567	1999/11/16	Apple Computer, Inc					✓	✓	✓
6002407	1999/12/14	Oak Technology, Inc				✓	✓	✓	✓
6016151	2000/1/18	NeoMagic Corp				✓	✓	✓	✓
6046747	2000/4/4	Hewlett-Packard Development Company, L.P				✓	✓	✓	✓
6166748	2000/12/26	Nintendo Co., Ltd. & Silicon Graphics, Inc				✓	✓	✓	✓
6181352	2001/1/30	NVIDIA Corporation					✓	✓	✓
6259460	2001/7/10	Silicon Graphics, Inc						✓	✓
6333744	2001/12/25	NVIDIA Corporation						✓	✓
6489963	2002/12/3	Nintendo Co., Ltd					✓		✓
6577317	2003/6/10	Apple Computer, Inc							✓
6618048	2003/9/9	Nintendo Co., Ltd						✓	✓

Table 4 (continued)

Patent No.	Date	Organization	~1985	~1990	~1995	~2000	~2005	~2010	~2015
6624813	2003/9/23	Sunplus Technology Co., Ltd					✓		
6636214	2003/10/21	Nintendo Co., Ltd					✓		
6693639	2004/2/17	Apple Computer, Inc							✓
6771270	2004/8/3	Hewlett-Packard Development Company, L.P					✓		
6809732	2004/10/26	NVIDIA Corporation							✓
6833831	2004/12/21	Sun Microsystems, Inc					✓		
6864892	2005/3/8	Sun Microsystems, Inc					✓		
6864893	2005/3/8	NVIDIA Corporation						✓	
6897871	2005/5/24	ATI Technologies, Inc						✓	
6980209	2005/12/27	NVIDIA Corporation						✓	
7224359	2007/5/29	NVIDIA Corporation							✓
7570267	2009/8/4	Microsoft Corporation						✓	
7633506	2009/12/15	ATI Technologies ULC						✓	
7755631	2010/7/13	NVIDIA Corporation						✓	
7777748	2010/8/17	Lucid Information Technology, Ltd							✓
7817151	2010/10/19	Via Technologies, Inc						✓	
7830392	2010/11/9	NVIDIA Corporation							✓
8189007	2012/5/29	Samsung Electronics Co., Ltd							✓
8427490	2013/4/23	NVIDIA Corporation							✓
8619087	2013/12/31	NVIDIA Corporation							✓
8624906	2014/1/7	NVIDIA Corporation							✓
8687008	2014/4/1	NVIDIA Corporation							✓
8698817	2014/4/15	NVIDIA Corporation							✓

the main paths are determined as time passes. In this research, it can be said that the technologies that are locked in are determined within ten years. Though almost all nodes that are observed on the main paths twice consecutively at five-year intervals did not drop out from the main paths in the long term, there is an exception: Patent 4945500. This patent is observed on the main paths in 1990 and 1995 but dropped out in the long term. This exception suggests that five years is not enough to determine which technologies are locked-in.

In Fig. 12, the change in the number of patents that are on the main paths and the change in the number of organizations that have patents on the main paths are presented. In this figure, Patent 5422998 is included in the line of the number of patents, but this patent is not included in the line of the number of organizations since this patent was not assigned to any organization. From 1985 to 2015, the number of patents that are on the main paths became almost three times as large in thirty years. In addition, as shown in Fig. 1, from 1985 to 2015, the total number of patents in this technological field became 122 times as large in thirty years. On the other hand, from 1985 to 2015, the number of organizations that have patents on the main paths became only one and a half times as large. Furthermore, the number of organizations that have patents on the main paths did not change much after 1995. These observations suggest that the number of organizations that can hold patents on the main paths is limited.



**Fig. 12** The change in the number of patents that are on the main paths and the change in the number of organizations that have patents on the main paths

Appearances and disappearances of nodes are appearances and disappearances of companies that own the patent at the same time. Some patterns of the appearances and disappearances of companies owning patents on the main path are also observed. Three companies are taken as examples of these patterns, International Business Machines Corporation, Hewlett-Packard Development Company, L.P., and NVIDIA Corporation. First, on the main paths of the period from 1975 to 2015, International Business Machines Corporation had three patents that appeared from 1990 to 1994, which was the early stage of the technological field. This company had no patents outside this period. This observation suggests that International Business Machines Corporation contributed to the establishment of this technological field, but they are no longer one of the main players. Second, Hewlett-Packard Development Company, L.P. had some patents toward the end of the main paths of the period from 1975 to 2000 and from 1975 to 2005. On the other hand, on the main paths of the period from 1975 to 2015, this company had no patents. Based on this observation, it can be said that Hewlett-Packard Development Company, L.P. once entered the mainstream of the technological field, but dropped out. Third, NVIDIA Corporation had twelve patents on the main paths of the period from 1975 to 2015 and all these patents were published after 2001, which is in the latter half of the history of the technological field. This observation suggests that NVIDIA Corporation became a main player in the technological field in the latter half of this history. These observations are consistent with the history of the technological field of computer graphic processing systems. In 1987, International Business Machines Corporation introduced a graphics accelerator called IBM 8514/A, which was the first widespread fixed-function graphics accelerator [31]. Thus, International Business Machines Corporation was a key player in the technological field of computer graphic processing systems and contributed to the establishment of this technological field, but now they no longer manufacture GPUs. Hewlett-Packard Development Company, L.P. manufactured graphics accelerator products called the Visualize-fx series around 2000, but now they no longer manufacture graphics accelerator products. Therefore, Hewlett-Packard Development Company, L.P. entered the mainstream of the technological field for a short period but dropped out. Even though they produced graphics accelerator products, Hewlett-Packard Development Company, L.P. has never been a key player in this industry. This is consistent with the observation that the patents that Hewlett-Packard Development Company, L.P. holds are placed toward the end of the main paths. As mentioned in Section 3, in 2001, NVIDIA Corporation released the Geforce 3, which was the first GPU product that implemented the programmable pipeline [29]. The programmable pipeline allows programmers to operate data while in the pipeline. The programmability of GPUs progressed from this year. At the same time, NVIDIA Corporation became the leader in this technological field from around 2001. Thus, observations of the appearances and disappearances of companies that hold patents on the main path are consistent with the history of the technological field.

## 6 Concluding Remarks

In this paper, technological development within the technological field of computer graphic processing systems was analyzed from the viewpoint of technological trajectories. The patent citation network data set of patents which are classified under the class US Patent Classification (USPC) 345/501 (inclusive) was used. Also, main path analysis was adopted to accomplish the goal.

In Sect. 4, the main paths were calculated using the method developed by Verspagen [2] and Liu and Lu [21]. In addition, the main paths were examined from the viewpoint of selectivity. Selectivity was observed on the firm level in the sense that the set of organizations that hold a large number of patents in the technological field was different from the set of organizations that hold patents on the main paths. Additionally, the fraction of patents the companies have on the main paths was larger than the fraction of patents the companies have on the whole citation network. On the other hand, selectivity in the sense that many patents converged to a small number of endpoints in the main paths was not as strong as that of the research case of the technological field of fuel cells examined by Verspagen [2]. The authors also found that there is a trend in the appearance of organizations in the main paths. This trend suggests that the most critical role of technological development is played by a single organization and the organization which plays this role changes through time. What this trend means will be examined in future research.

In Sect. 5, main path analysis on patent citation network datasets was repeated for different periods. Using this method, the “snapshots” of the main paths over time were obtained. According to this observation, patterns of nodes’ appearances and disappearances on main paths could be seen. First, all nodes that were observed on the main paths three times consecutively at 5-year intervals did not drop out from the main paths in the long term. Second, most of the appearances and disappearances of the nodes occurred toward the end of the main paths. These observations are consistent with the technological lock-in process. This research indicates that it takes less than 10 years to determine which technologies are locked-in. In addition, various patterns of the appearances and disappearances of companies owning patents on the main paths were also observed. Three companies were used as examples to illustrate these patterns. Additionally, the change in the number of organizations that have patents on the main paths suggests that the number of companies that can survive in the mainstream of an industry and can hold patents on the main paths is limited.

This research has implications for technology management. The result of this research suggests that it takes less than ten years to determine which technologies are locked in. According to this result, to make a patent locked-in a part of the technological standard in a field, companies should keep their technology on the mainstream of the technological field for at least ten years.

As mentioned in Sect. 4.2, this research found a trend in the appearance of organizations in the main paths in the year 2015. For example, from 2001 to 2014, twelve patents out of twenty patents were owned by NVIDIA Corporation,

which did not appear on the main paths before 2001. This trend suggests that publishing patents in a combination could be a factor for technological lock-in. Though how technological trajectories are formed is examined in this research, the factors in the formation of technological trajectories are not examined. The authors will examine the factors in the formation of technological trajectories in future research.

This research has a limitation because of the data selection. In this research, only patents that are classified under the class US Patent Classification (USPC) 345/501 (inclusive) are examined. Patents that are not classified under this class and works of academic literature are not included in the data set even if they are related to computer graphic processing systems. For example, patents which are classified as Class 382 are about image analysis, which is a subject that is strongly related to computer graphic processing systems. However, they are not examined in this research to keep the data manageable. Thus, in this research, technological evolution outside the class US Patent Classification (USPC) 345/501 (inclusive) is not examined. Future research may consider the issue of how other patents and works of academic literature contribute to the technological evolution of graphic processing systems.

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