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RECENT ADVANCES IN GRAPH THEORY AND ITS APPLICATIONS: EXPLORING TECHNIQUES AND REAL-WORLD IMPLEMENTATIONS

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ABSTRACT

Graph theory is a sophisticated mathematical framework for studying the characteristics and connections of graphs, which are collections of nodes and edges. Significant advancements have been made in graph theory and its applications in recent years, leading to novel techniques and real-world implementations. This abstract provides an overview of these recent advances. One notable development is the emergence of Graph Neural Networks (GNNs), which enable learning graph-structured data representations. GNNs have been successfully applied in various domains, including node classification and link prediction.Community detection algorithms have also improved accuracy and efficiency, benefiting social network analysis and other related fields. Graph embedding techniques have also progressed, facilitating learning low-dimensional vector representations for nodes or subgraphs. This advancement has enhanced tasks such as link prediction and node classification. Furthermore, temporal graph analysis has gained attention for studying dynamic graphs, allowing for predicting future states and anomaly detection. The application of graph theory in social networks has yielded valuable insights into sentiment dynamics, influence maximization, and information diffusion. These findings aid in understanding social behaviour and designing effective interventions. Network alignment and graph matching techniques have been developed to integrate and analyze data from multiple sources, finding applications in diverse fields, including biological networks and cross-domain data analysis. Graph theory has significantly contributed to transportation and urban planning, addressing challenges like traffic flow optimization, route planning, and public transportation design.Furthermore, the application of graph theory in bioinformatics and drug discovery has led to advancements in drug-target interaction and protein function prediction. Recent advances in graph theory have opened up new avenues for research and practical applications. The growing availability of large-scale graph data and the need to extract insights from complex interconnected systems continue to drive the evolution of this field. These advancements hold great potential for addressing real-world challenges across diverse domains.

***Keywords**: Community Detection, Influence Maximization, Network Embedding, Temporal Graphs, Graph Databases*

I. INTRODUCTION

Applications in the field of computing make extensive use of the principles of graph theory. Data mining, picture segmentation, clustering, image capture, networking, etc., are all active areas of study in computer science. A tree-shaped data structure, for instance, would use nodes and links to organize its data. Network

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topologies may also be modelled using graph ideas. Resource allocation and setup both make use of graph colouring's central idea. In graph theory, excellent applications include the travelling salesperson problem, database design principles, resource networking, use of pathways, walks, and circuits. This results in creation of cutting-edge algorithms and theorems with far-reaching practical implications.

For many situations in the actual world, a diagram may be described simply by including numerous points and lines that connect many pairs of these points. The points may represent people with lines connecting them to romantic partners or close friends or contact centres with lines depicting other kinds of relationships between them and the outside world. In such diagrams, the way the lines are joined is secondary to whether or not they connect two designated locations. Graph theory provides a statistical abstraction of such situations. Graph theory concepts are widely used in many disciplines for analysis and simulation. The study of atoms, molecules, and chemical bonding all fall under this umbrella. Graph theory has many applications in the social sciences, including the study of networks and the study of how ideas spread from one place to another. The theory of graphs is used for the preservation of biodiversity, with vertices representing habitats and edges representing routes of movement between habitats. This information is crucial for studying the transmission of diseases and parasites and the impact of migration on other species. You must know this. Graph theory ideas are ubiquitous in the realm of computing [1]. “Breadth First Search, Depth First Search, Topological Sort, Bellman-Ford, the algorithm of Dijkstra, Minimum Trees, the Algorithm of Kruskal, and Prim's algorithm are all examples of algorithms used in graph theory.”

II. HISTORY OF GRAPH THEORY

The Koinsber bridge problem of 1735 is considered the progenitor of the graphic principle. The Eulerian Graph Theorem may be derived from this conundrum. In order to address the Koinsberg Bridge issue, Euler developed the Eulerian graph. In 1840, A.F. Mobius introduced the ideas of a total and a bi-partisan graph; later, Kuratowski proved that both graphs were planar concerning leisure-time issues. Current in electrical networks or circuits may be measured using the tree principle (Gustav Kirchhoff created a connected graph without cycles in 1845) and other graphical technical notions. Thomas Gutherie uncovered the four-colour printing error plaguing readers since 1852. 1856 Thomas, P. Kirkman, and William Hamilton studied polyhedra cycles. He came up with the concept of the Hamiltonian graph after seeing that some journeys went to several different sites only once. H. Dudeney addressed a riddle problem in his 1913 talk. After a century, Kenneth Appel and Wolfgang Haken tackled the problem of the four colours. The foundations of graph theory were laid [2]. Caley mastered several analytic forms from differential calculus to study the trees. Moreover, this has several ramifications for theoretical chemistry. This motivates the development of enumerative graph theory. In any case, Sylvester proposed a "Graph" in 1878, making connections between "quantum invariants" and the covariants of algebraic expressions and molecular diagrams [3]. Ramsey began his colour experiments in 1941, eventually recognising the field of study now known as severe graphic theory. The puzzle of the four primary colours was solved by Heinrich's computers in 1969. The study of asymptotic graph connection has led to the discovery of a random graphic design concept.

III. APPLICATIONS OF GRAPH THEORY

The ideas of graph theory are widely used to study and simulate various applications. This encompasses the study of atoms, molecules, and chemical bonding. Graph theory also has applications in the social sciences, such as studying diffusion processes and determining a performer's fame. In biology and conservation, diagrams show where different species live and where their migrations and other movements take them. This information is vital for studying migratory patterns, tracking the spread of illnesses and parasites, and

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understanding the impact of migration on other species [4, 5]. Principles of theoretical graphics are often used in scientific investigations. Finds the shortest path between two nodes and solves problems like the tour salesperson's conundrum and the little stretch in a weighted network. Other applications include simulating transportation systems, business networks, and game theory[6]. The finite-game approach is represented as a digraph. In this case, the vertices indicate the places and the edges of the paths taken. Graph theory has several applications in science and engineering. Given any of the following:

A. *Computer Science*

The theory is used in computer graphics to examine algorithms like the Dijkstra Algorithm, the Prims Algorithm, and the Kruskal Algorithm. The application domains used to define the computation flow include graphs. Communication webs may be represented using graphs. Graphs illustrate the structure of the findings. Rules-based graph manipulation is the foundation for graph transformation methods. Graph databases provide reliable, always-available storage and querying for structured graph data. The fastest path across a network may be determined with the help of graph theory. In Google Maps, locations are represented as vertices or points, while corners represent roads; this representation is used to calculate the shortest route between any two given points.

B. *Electrical Engineering*

In electrical engineering, graph theory is used to build circuit linkages. Topologies are used to describe these kinds of connections. Examples include sequence topology, bridge topology, star topology, and parallel topology.

C. *Linguistics*

In linguistics, graphs are often used for the parsing of language trees and grammar for language trees. Lexical semantics uses semantic networks, which are very useful for computers, and makes it easier to model the meaning of words by interpreting them in context. As a diagrammatic tool, phonological analysis (such as optimum theory) and morphological analysis (such as finite-state morphology using finite-state transducers) are widely used in the study of languages.

D. *Physics and Chemistry*

Chemical compounds may be represented as graphs in chemistry. To resolve inconsistencies between two sequences, statistical biochemistry permits the omission of any sequence of cell samples. This is represented as a directed graph, with the sample sequences serving as vertices. When there is a collision between the sequences, an edge is drawn between the two conflicting vertices. The plan is to get rid of all disagreements by eliminating possible vertices, which are sequences. In brief, graphic theory significantly impacts various contexts and rapidly expands throughout a wide range of periods. The following section provides an in-depth examination of how graph theory is used in computing. In physics and chemistry, molecules are analyzed using chart theory. Statistics on graph-theoretic properties in connection to atom topology allow for quantitative analysis of the 3D layout of complicated artificial atomic systems. Statistical mechanics also make use of graphs. In this field, diagrams depict the local connections between the interacting parts of a system and the dynamics of the underlying physical processes. Porous media microchannels may be expressed as graphs, with the vertices representing the larger pores and the boundaries representing the smaller pores. The molecular structure and molecular grid may benefit from using a graph. It also enables us to compare the structures of different molecules and show how atoms are connected to them.

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E. Computer Network

In a computer network, the connections between nodes follow the rules of graph theory. When it comes to keeping networks safe, graph theory is often used. We will use the vertex colouring technique to colour the map in four hues. It is possible to assign up to four unique frequencies to any GSM (Grouped Special Mobile) mobile network using the Vertex Colouring Algorithm.

F. Social Sciences

The field of sociology also makes use of graph theory. For instance, social network analysis methods may probe how rumours spread or how credible specific individuals are. Their friendship and knowledge graphs describe the connectivity between people. Certain people can influence the actions of others in impactful diagrams. Using the collaborative graphs approach, two people work together in a familiar setting, such as watching a movie.

G. Biology

Bimolecular entities (such as chromosomes, proteins, or metabolites) serve as the "nodes" in biological networks, while the "edges" connecting the nodes represent the interactive, physical, or chemical interactions between the nodes. Graph theory is used for transcriptional regulation networks. It is also seen in metabolic networks. Protein-protein interaction (PPI) networks are another use of graph theory. Partnerships that share a drug-related objective. Synergistic Effects of Drugs.

H. Mathematics

The cornerstone of mathematics is operational analysis. Graph theory has several applications in the field of organizational analysis. Minimum travel costs, The timetable has a problem. The lines represent the highways that connect the cities. With the help of a certain kind of graph, we may build hierarchically organized information like a family tree.

IV. PROBLEMS IN GRAPH

Enumeration

Graphical listing, or the issue of how many graphs there are that satisfy the stated requirements, has generated a large body of research. Harary and Palmer [6] present some of the results of this study.

Sub-graphs, induced sub-graphs, and minors

A common issue has a fixed graph as a subgraph in a given graph, called the subgraph isomorphism issue. A justification for being concerned is that specific graph properties for subgraphs are inherited, implying that a graph only owns the proprietorship if other subgraphs have the value. Sadly, it is always an NP-complete question to locate maximal subgraphs of a certain kind. Examples include:

- Clique problems have the maximum complexity and are thus NP-complete.
- Graph isomorphism is a subset of the broader subgraph isomorphism issue. It raises doubts about the isomorphism of the two diagrams. It is possible that we do not know whether this issue is NP-complete or if it can be solved in polynomial time.
- Similarly, mediated segments of a particular graph are identified. Again some essential graph properties for induced subgraphs are inherited, implying that a map has a property only if they are all caused by all the caused subgraphs. Also, NP-complete is always the maximum mediated subgraphs of a certain kind. For instance:

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- A different collection (NP-Complete) problem is the most edgeless influenced subgraph or isolated group.
- Another problem, the minor confinement issue, is having a fixed graph as a minor of a specific diagram. Every graph generated by taking a subgraph and contracting a few (or no) edges are a minor or subcontract. Most charts are passed to minors, meaning a character is only held if all minors share it. Wagner's Theorem states, for instance:
- A portion of the network is planar as it does not include the complete two-part map K3,3 or the complete map K5 as a minor.
- A related challenge is considering a defined diagram as a subset of a specified map, the challenge of a containment subset. Every graph generated by subdividing (or not) edges is a subset or homomorphism of a graph. The isolation of subdivisions is related to properties like planarity. For example, the theorem Kuratowski states:
- A diagram is flat because it does not contain a complete division K3,3 or a complete diagram K5 as a section.
- The Kelmans-Seymour assumption is another problem with unit containment:
- A subset of a 5-vertex graph K5 is used with a 5-vertex graph that is not planar.
- Another type of issue is linked to how many species are defined from their point-deleted subgraphs and to generalizations of maps. For instance:
- Speculation on reconstruction

Graph colouring

Several problems of graph theory and theorems apply to different colouring strategies of graphs. In general, you are interested in painting a graph such that there are no two neighbouring vertices with identical hues. Coloured edges (possibly such that no two edges are the same colour) or other differences can also be seen. The following are some of the famous findings and conclusions regarding graph colouring:

- The Erds-Faber-Lovász conjecture is still open, as is the Four-Color Theorem and the Strong Perfect Graph Theorem.
- Behzad's hypothesis (unresolved) on total colouring.
- The (unresolved) List Colouring Conjecture
- The unanswered Hadwiger hypothesis in graph theory

Subsumption and unification

The theory of restricted design refers to families of graphs connected to a limited sequence. In such applications, graphs are organized so that more narrow graphs are subdivided into more general, more complex graphs, which contain more details. Machine graph integration and evaluating the route of a subsumption connection between two graphs are examples of graph operations. Effective unification methods are devised, and the most generic graph, i.e. incorporating all information in) the inputs, is defined as the result of unifying two argument graphs. Without the actual graph, just a single graph description is given.

Graph fusion adequately fulfils and combines functions for restrictive structures that are purely compositional. Automatic hypothesis checking and modelling the creation of language structure are well-known applications.

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Route problems

- Problems like the Hamiltonian path issue, minimum spanning tree, and the route inspection problem (sometimes known as the "Chinese postman problem") are all examples.
- The Steiner tree, the Three-Castle Problem, the Travelling Salesman Problem, and the Seven Bridges of Königsberg are all examples of NP-hard problems.

Network flow

Systems of diverse conceptions of network flows are facing multiple difficulties, for instance:

- Maximal Flow Minimum Cut Theorem

Visibility problems

- Issues with Museum Security

Covering problems

Graphic coverage can apply to specific set coverage problems on vertical / subgraphs subsets.

- The prevailing issue in package covers is the unique case where the collection is closed.
- The problem with the cover vertex is the case with the frame cover, where the sets are all sides.
- The initial set cover issue can be represented as a vertex cover in a hypergraph, often called a hitting set.

Decomposition problems

There is a wide variety of concerns related to decomposition, defined as partitioning a graph's edge set (the number of vertices following each part's edges, as required). This is also required when subdividing a whole diagram into smaller subdiagrams, such as Hamiltonian cycles, that are isomorphic to the original. For example, many issues require decomposing a Kn network into n1 specified trees with 1, 2, 3,..., n1 edges, where n is the number of edges in the graph.

Among the many decomposition issues that have been examined are the following:

- Arboricity, decomposition to the fewest available trees
- Double loop wrapping, decomposition into loops that are precisely two-fold on each side
- Layer painting, decomposing in the fewest practicable matches
- Factorization of the line, decomposition of an ordinary line into average graphs

V. RESULTS

A. *Overallstatisticsanddistributions*

Our query was matched by 1280 unique documents. We couldn't include one of the publications that was later retracted. In all, 7121 references to these works have been made elsewhere. This means that, on average, there are 5.56 citations per document. The distribution of the various document kinds is shown in Table 1. Reviews, conference papers, and articles (which together make up 96.24 percent of the data) have, on average, 49.44, 6.31, and 4.04 citations per publication.

TABLE1.Documentstypes

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Documenttype	Number	Averagecitationsperpaper
ConferencePaper	854	6.31
Article	369	4.04
ConferenceReview	38	2
Review[4]	8	49.44
BookChapter[5]	8	0.25
Note	1	1
Book	1	0

The upward trajectory of these papers' publication is seen in Figure 1. First published in 2004 by Scarselli et al. [7] in Lecture Notes in Computer Science (which includes subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), the earliest work in our document collection goes back to 2004. The paper's authors, Scarselli, Tsoi, and Gori, are all highly regarded experts in their respective fields. They developed a structure that is analogous to recursive neural networks, in which each unit remembers the state of the nodes in the network and, when activated, predicts the state of the network based on the states of its neighbours.

Before 2017 there were just 41 total documents released. After then, there was a massive increase in the number of papers written on this topic. This area of study is obviously extremely new and rapidly growing in importance. Figure 1 displays the annual growth in citations to articles published in that year. For instance, the graph shows that publications published in 2017 are referenced by subsequent papers roughly 1800 times. Before 2017, the citations curve shows two distinct local maxima, in 2005 and 2009. Gori et al. [8] and Scarselli et al. [9] are primarily responsible for them. Li et al. [10] has been cited more often in 2016 than in previous years. The year 2017 marks a major turning point, as the quantity of citations has skyrocketed. This year also saw the publication of some highly-referenced works, such as [11] and Bronstein et al. [12]. Many influential works, such as those by Yan et al. [13], Schlichtkrull et al. [14], Ying et al. [15], and Zhang et al. [16], were published in 2018. AlQuraishi[16], Wang et al. [18], and Zhang et al. [19] are just a few of the exceptional papers that have appeared in 2019.

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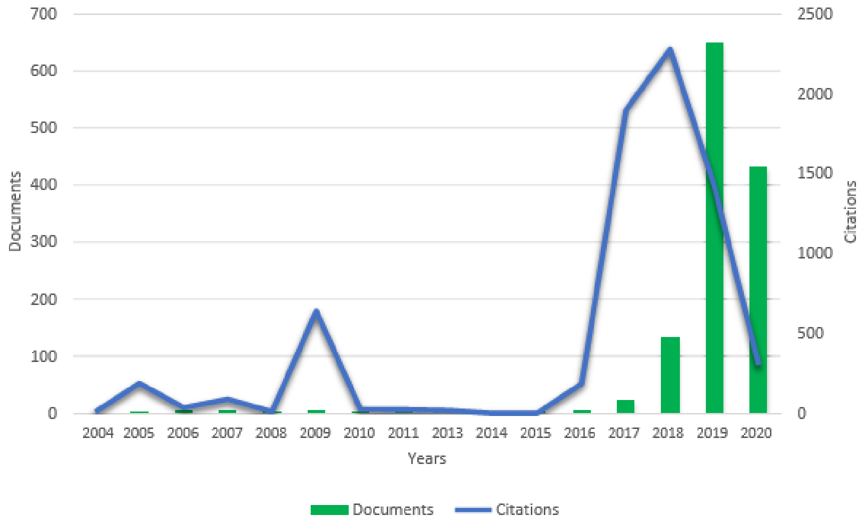

Figure1.Yearlynumberofdocumentsandcitations

Figure 2 displays the breakdown of GNN articles by topic across all 22 categories. Information Technology (86%) is followed by Mathematics (22.90%), Engineering (22.59%), Decision Science (10.16%), Social Science (8.44%), Materials Science (5.16%), Physics and Astronomy (4.76%), Biochemistry, Genetics, and Molecular Biology (3.98%), Business, Management, and Accounting (3.67%), and Arts and Humanities (3.67%).

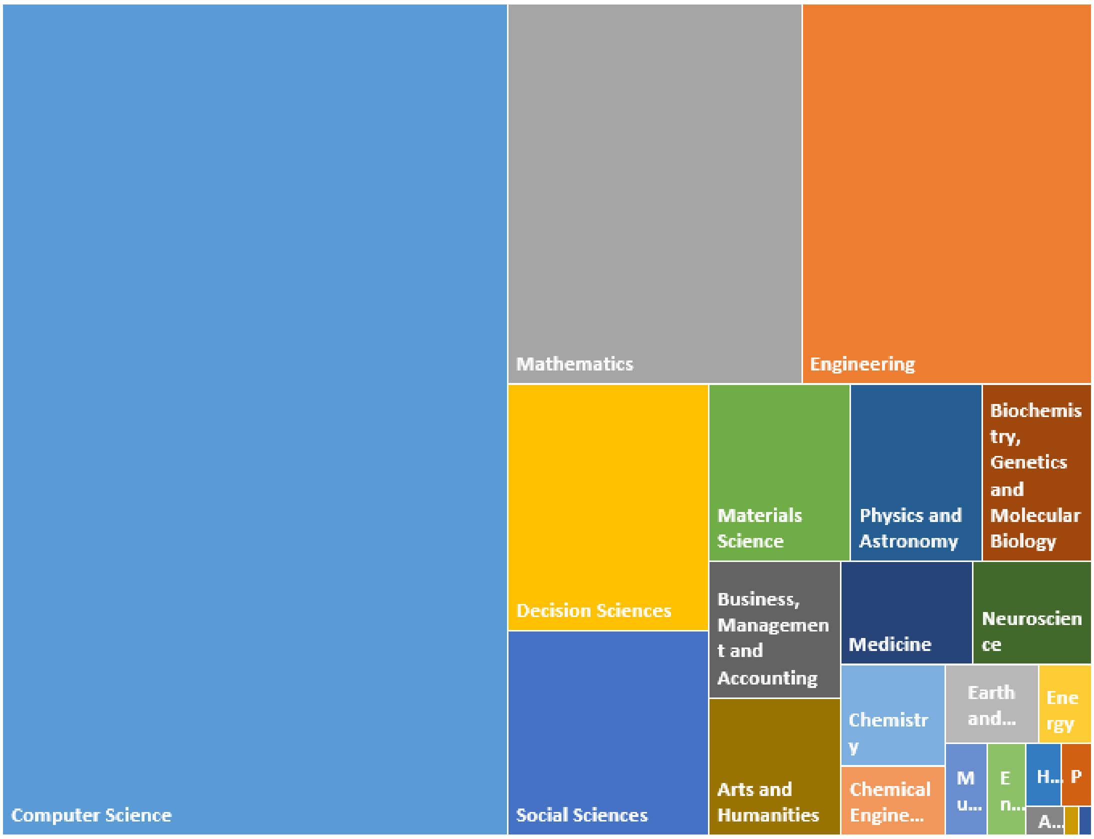

Figure2.Differentsubjectcategories

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B. Scientificcollaboration

The average number of authors per manuscript is 5.73, according to an analysis of co-authorship trends. Number of authors and average citations per manuscript distribution are shown in Figure 3. The study by Sügis, et al. [20] has the most authors (18) working together. We can see that the average number of citations per manuscript decreases after a certain number of authors, with the exception of those with five or more names on the publication. On average, there are 5.75 citations per collaborative article compared to 3.82 citations per single-author work.

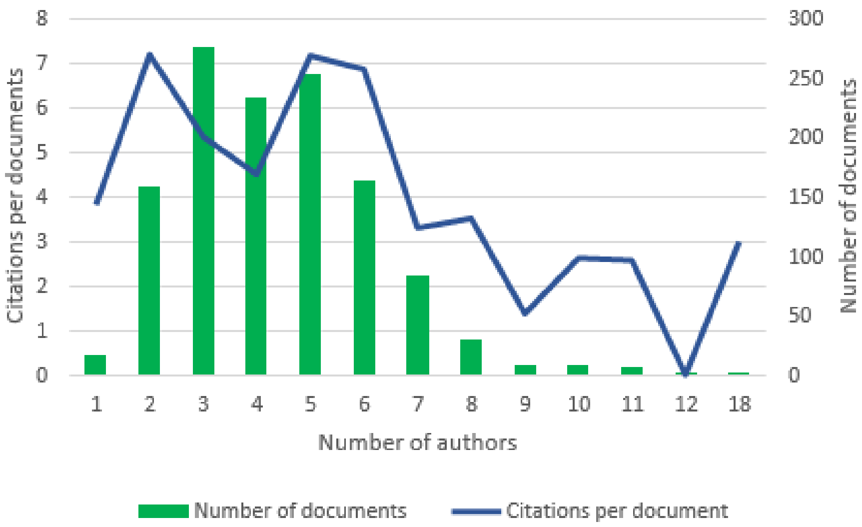

Figure3.Distributionofthenumberofauthorsandtheaveragenumberofcitationsperdocument

C. Topcountriesandinstitutions

Fifty-one different nations' citizens wrote various GNN papers. The United States (377 papers), China (377 documents), and Canada (82) published the most in this area, while China published the most overall (593 documents). Error! Error locating referenced material. provides a map of international cooperation that highlights the world's 10 most productive nations. The number of documents published per nation is represented by the size of the nodes in the graph. The graph's edges represent collaboration, while the nodes' hues signify groups of related ideas. Clustering has been done using VOS algorithm [21] based on cooperation. The geographic distribution helps explain the six distinct groups. European nations in the first cluster include the familiar names of the Netherlands, Belgium, and Spain. Three Asian nations and the United States and Germany make up Cluster 2, making it the most diverse of the two. East Asian nations like China, Japan, and South Korea make up the third group. Cluster four includes the knowledge-sharing nations of Hong Kong, Australia, and Italy in East Asia and Europe. The United States also clearly serves as a link between China and European nations. Cluster 5, which includes Singapore in Southeast Asia, Israel in the Middle East, and Switzerland in Northwestern Europe, does not follow any distinct geographical trends. Cluster 6 consists of the countries of Ireland (Northwestern Europe) and Canada (North America).

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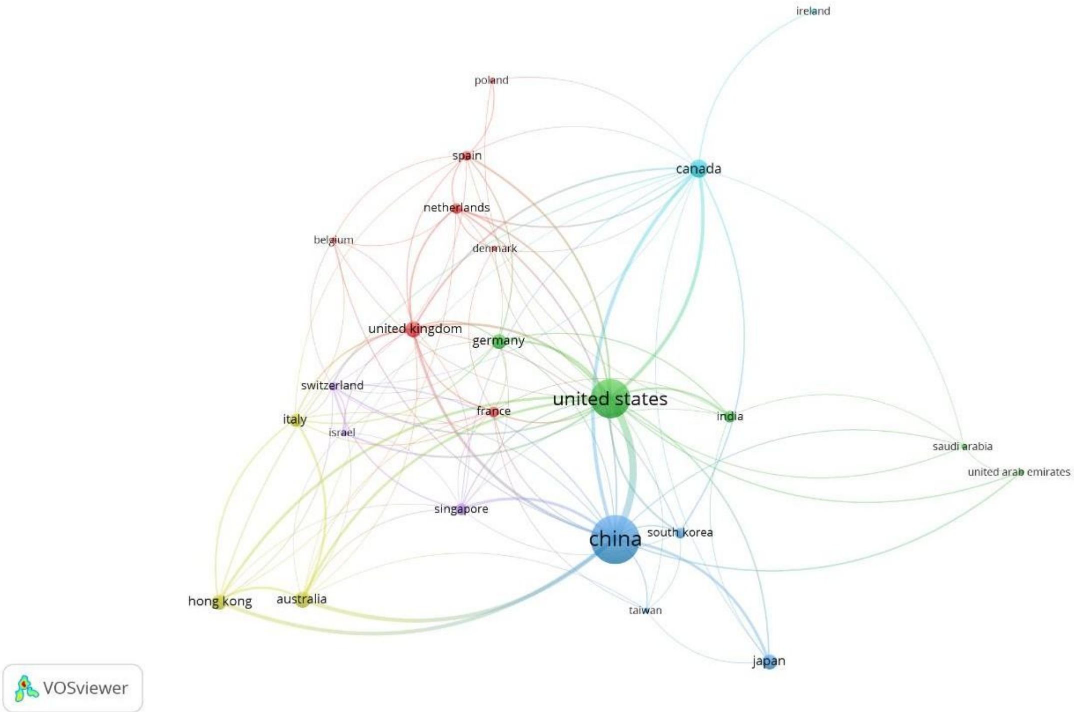

Figure4.Topcountriesscientificcollaboration

The 10 most productive and influential organisations in this area are shown in Table 2. As may be anticipated from a country with China's population and scientific output, Chinese organisations have released a large number of documents. Only one Italian university made the list of the top ten most productive universities. However, most of the most-cited sources are located in either Europe or the United States. Most citations are associated with the University of Amsterdam. Researchers like Thomas Kipf, Max Welling, and Ivan Titov have made significant contributions to prominent models and produced widely-cited articles while working at this institution. It's worth noting that Facebook studies have started showing up at some of the world's most prestigious academic institutions.

Table2.Topinstitutions

Mostprolific			Mostimpactful		
Institution	Country	Docs	Institution	Country	Citations
ChineseAcademyofSciences	China	87	UniversityofAmsterdam	Netherlands	975
UniversityofChineseAcademy ofSciences	China	67	UniversityofSiena	Italy	944
TsinghuaUniversity	China	43	CanadianInstituteforAdvanced Research	Canada	767
PekingUniversity	China	41	UniversityofWollongong	Australia	714
BeijingUniversityofPostsand Telecommunications	China	31	HongKongBaptistUniversity	HongKong	651

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InstituteofAutomationChinese AcademyofSciences	China	29	NewYorkUniversity	United states	492
BeihangUniversity	China	29	UniversitadellaSvizzeraItaliana	Italy	459
Tencent	China	28	Facebookresearch	United states	435
ShanghaiJiaoTongUniversity	China	23	SwissFederalInstituteof TechnologyinZurich	Switzerland	435
UniversitàdegliStudidiSiena	Italy	23	UniversitécatholiquedeLouvain	Belgium	435

VI. CONCLUSION

This work provided a bibliometric survey of the burgeoning but still-young topic of graph theory. Based on the current trajectory of scientific publications, it's clear that GNNs have captured the imagination of the scientific community.The most influential publications in this discipline are conference papers. One of the pioneers in the subject of GNN study is Franco Scarselli, who also contributed to the very first article on the topic.

China is home to many bustling institutions, but Europe and the United States are where you'll find the most influential ones. Computer Science Lecture Notes, covering related series The majority of GNN studies have been published in the series Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics.

Node classification is the most common job according to the most searched terms, followed by link prediction and graph classification. In addition, the popularity of related search terms suggests that the attention mechanism is in the spotlight.

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