Physical Theories of the Evolution of Online Social Networks: A Discussion Impulse

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***Abstract*—The evolution of online social networks (OSN) is a hot topic in computer science. Surprisingly a lot of research on this topic was also done by physicists – following the long history of studying networks in physics. To give an interdisciplinary discussion impulse, this paper intends to delineate the major physical theories of the evolution of (O)SN. Furthermore the paper presents a future research gap, which consists in the lack of adoption of the physical theory of preferential attachment on OSN by computer scientists.**

***Keywords-online social networks; evolution; physical theories; interdisciplinary perspective*.**

I. INTRODUCTION

In the last years, there has been a lot of research activities on OSN in different disciplines (e.g., computer science [1], [2], economics [3], sociology [4], and psychology [5], [6]). Understanding the structure of OSN, as well as the processes that shape them, is regarded as important [7]. "It would be useful to have efficient algorithms to infer the actual degree of shared interest between two users, or the reliability of a user (as perceived by other users). With respect to security, it is important to under- stand the robustness of such networks to deliberate attempts of manipulation [7, p. 31]."

One of the main research aims concerns the evolution of OSN. Despite of the rich spectrum of the mentioned disciplines there are huge differences in saturation on OSN evolution research. Therefore, three databases were queried on 19th August and 20th August 2011: ACM Digital Library, IEEE Xplore Digital Library and ISI Web of Knowledge. Search terms were 'evolution social networks', 'social network theory internet', 'social networks evolution internet' and 'evolution social network internet'. The selection criterion was 'most cited' on IEEE Xplore Digital Library, 'times cited' on ISI Web of Knowlegde and 'citation count' on ACM Digital Library. Searched were in abstract, title and content of articles. To complete these results, the databases ScienceDirect and SpringerLink were also queried on 3rd September 2011 for 'relevant' articles. Between all the findings were selected the 15 most relevant articles. The relevance was evaluated with regard to the abstracts. An article, that had been comparatively less quoted, was preferred under certain circumstances to a more often cited article, because of its ability to answer the research question.

Table I
15 MOST RELEVANT ARTICLES

TITLE
A comparative study of social network models: network evolution models and nodal attribute models [8]
Emergence of a small world from local interactions [9]
Empirical analysis of an evolving social network [10]
Evolution of a large online social network [11]
Evolution of the social network of scientific collaborations [12]
Measurement and analysis of online social networks [7]
Microscopic evolution of social networks [13]
MySpace and Facebook: applying the uses and gratifications theory to exploring friend-networking sites [14]
Properties of on-line social systems [15]
Self-similar community structure in a network of human interactions [16]
Social Networking [17]
Structure and evolution of online social networks [18]
Structure and time evolution of an Internet dating community [19]
The Evolution of Social and Economic Networks [20]
The structure and function of complex networks [21]

The research revealed a great interest of the physicist community: six of the most relevant 15 articles were published in physical journals, including the most relevant article. Further articles came from Computer Science (4), Economic Theory (one), Mathematics (one), Psychology (one), Science (one), and Social Networks (one). For control purposes the database ISI Web of Knowledge was again queried on 19th November 2011. The queried terms were 'evolution social network internet', the selection criterion was 'most cited', the subject of the research where the abstract, the title and the content of articles. The research also showed the great interest of physicists. Between the first 25 results came eight from physical journals. Here the list of the further ranking of sciences: Computer Science (six), Health (two), Law (two), Biology (one), Management Science (one), Marketing (one), Psychology (one), Science (one), Social Networks

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(one), and Telecommunications Policy (one). As a result of these inquiries, the research question was redefined in: How physical theories explain the evolution of OSN? This paper focuses on the OSN, seen through the glasses of physics.

Why physicists are interested in OSN at all? "The study of networks has had a long history in mathematics and the sciences... [22, p. 1]"– but the recent time brought a renewal: the advent of modern database technology, which can process even huge amounts of data [15, p. 107]. "Being far larger than the datasets of traditional social network analysis, these networks are more amenable to the kinds of statistical techniques with which physicists and mathematicians are familiar [22, p. 6]". At the end of the 1990s the investigation of massive amounts of data with mathematical and physical techniques marked the beginning of a "new science of networks [22, p. 4]" (leading theorists: Albert-László Barabási, Mark Buchanan, Duncan J. Watts and Mark Newman [23, p. 57]). According to Barabási, Newman and Watts the new science distinguishes itself from the previous work in three ways: first by focusing on the properties of real-world networks, second by looking networks as evolving structures and thirdly by considering networks as dynamical systems [22, p. 4].

A. Method and structure of the article

The literature-based work systematically investigated the most substantial relevant databases (ACM Digital Library, IEEE Xplore Digital Library, ISI Web of Knowledge, ScienceDirect, SpringerLink) with regard to the physical theories of the evolution of networks. The 15 most relevant articles present research findings referring on physical theories of the evolution of networks – but these articles do not explain these theories in detail. Therefore a mere presentation of the research results would be incomprehensible for a reader who is not a network theorist. That is why we structure the research findings on the basis of the article "Scale-Free Networks" by the physicists Albert-László Barabási and Eric Bonabeau [24] who provide an introduction to current physical theories of the evolution of networks. This article is used as a framework for the general explanation of certain topics, which are then refined by the findings in the 15 most relevant articles.

The paper is organized as follows. Section II introduces the relevant terms. Section III discusses physical theories of the evolution of networks and their application on OSN. Section IV lectures criticism on the the physical theories about OSN. Section V explores how the physical theories of the evolution of OSN are adopted by computer scientists. Section VI shows limitations of this paper, presents a future research gap and open issues.

II. Clarification of terms

Evolution is considered as "the development or growth, according to its inherent tendencies, of anything that may be compared to a living organism (*e.g.,* of a political constitution, science, language, etc.); sometimes, contrasted with *revolution*. Also, the rise or origination of anything by natural development, as distinguished from its production by a specific act; 'growing' as opposed to 'being made' [25, p. 477]." A network is "a set of items, which we will call vertices or sometimes nodes, with connections between them, called edges... [21, p. 168]." A social network is a "set of people or groups of people with some pattern of contacts or interactions between them... [21, p. 172]." The term OSN is used in the sense of a social-networking site, defined by boyd and Ellison: "We define social network sites as web-based services that allow individuals to (1) construct a public or semi-public profile within a bounded system, (2) articulate a list of other users with whom they share a connection, and (3) view and traverse their list of connections and those made by others within the system. The nature and nomenclature of these connections may vary from site to site [1, p. 211]." Physical terms are explained in Section III, directly when physical theories are presented. The term OSN is always used in plural. The terms vertex and node are congruent.

III. Physical Theories on OSN

Among the 15 most relevant articles are [7], [11], [13], [15], [18] and [19] of particular interest: they are empirical studies that apply current physical theories of the evolution of networks on OSN – in the sense of definition of OSN given in Section II. Covered OSN are the Swedish community Pussokram.com [19], the Polish community Grono.net [15], the Community of the Polish Massive Multiplayer Online Role Playing Game Allseron.com [15], LastFM [15], the books admirer community Shelfari [15], Flickr [7], [13] and [18], YouTube [7], LiveJournal [7], Orkut [7], Yahoo 360^{o} [18], Delicious [13], Yahoo Answers [13], LinkedIn [13] and the Chinese business community Wealink [11]. Other research subjects were databases of journals [12], email communications within universities [10] and [16] and communications via XFire, an instant messaging service for gamers [15].

A. Power-law distribution of vertex size

Barabási et al. experimented in 1998 with software to map how Internet sites are connected [24, p. 62]. The sites were sorted according to their size (the number of their links). Barabási and Bonabeau [24] expected to find a Poisson distribution of sizes: that sizes cluster around a mean value and sites with much more or fewer links are likely to be an exception. But the measurements refute the expectation: More than 80 percent of sites had less than four links, but in a minority of less than 0.01 percent had each site more than a thousand links. According to these results the World Wide Web is held together by very few, very large connection-rich vertices. The sorting of the sites with regard to their

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size revealed a "power law": the probability that any site has exactly k links is roughly proportional to $1/k^n$. The associated distribution curve does not have the pronounced peak at the typical size, but "is instead described by a continuously decreasing function [24, p. 63]."

Among the 15 most relevant articles were found that distribution of node size – the number of their incoming and outgoing connections – on Allseron.com, Grono.net, LastFM and Shelfari follows the power-law scaling form [15, p. 107]. Also Flickr, LiveJournal, Orkut and YouTube "show properties consistent with power-law networks [7, p. 36]." The distribution of vertices according to their size of Flickr and Yahoo 360° [18, p. 613] and Wealink [11, p. 1107] revealed a power law. By focusing on the microscopic vertex behavior of Flickr, Delicious, LinkedIn and Yahoo Answers it was also analytically shown that the edge initiation process can be captured by exponential vertex lifetimes and a "gap model" based on a power law [13, p. 470]. The degree distribution of vertices on Pussokram.com does not "fits a power-law form across the whole range observed [19, p. 165]." The degree is the number of edges connected to a vertex. However, the authors refer to a study of the French OSN nioki.com that has reported a power-law of the cumulative degree distribution. They conclude that "a closer inspection of our graphs… reveals a striking similarity in the functional form of the distribution. We therefore conclude that the dynamics shaping the degree distribution is to a large extent the same for the two communities [19, p. 165]."

B. Scale-freedom

The term scale-free means: there is no vertex size, which could be considered as "normal" and thus could apply as a measure [24, p. 62]. "Over the past few years, investigators from a variety of fields have discovered that many networks – from the World Wide Web to a cell's metabolic system to actors in Hollywood – are dominated by a relatively small number of nodes that are connected to many other sites. Networks containing such important nodes, or hubs, tend to be what we call "scale-free," in the sense that some hubs have a seemingly unlimited number of links and no node is typical of the others [24, p. 62]." Among the 15 most relevant articles it was found that the OSN Flickr, LiveJournal, Orkut and YouTube show scale-free properties [7, p. 32]. The authors of [7] calculated a value called 'scale-free metrics' that stands between 0 and 1 and measures the extent to which the graph of an OSN has a hub-like core. "A high scale-free metric means that high-degree nodes tend to connect to other high-degree nodes, while a low scale-free metric means that high-degree nodes tend to connect to low-degree nodes [7, p. 38]." The values are 0.49 for Flickr, 0.34 for LiveJournal, 0.36 for Orkut and 0.19 for YouTube. "All of the networks with the exception of YouTube, indicating that high-degree nodes tend to connect to other high-degree nodes, and low-degree nodes tend to connect to low-degree nodes [7, p. 38]."

C. Preferential attachment

Barabási and Bonabeau [24] attribute scale-freedom to two causes. First the older a vertex is, the more opportunities it had to build links. Therefore, vertices tend to be greater the longer they have been in the network. The second cause was called "preferential attachment". New vertices are connected preferentially with the major vertices and therefore major vertices are getting greater and greater over time. "… as new nodes appear, they tend to connect to the more connected sites, and these popular locations thus acquire more links over time than their less connected neighbors. And this "rich get richer" process will generally favor the early nodes, which are more likely to eventually become hubs [24, p. 65]."

Among the 15 most relevant articles the authors of [13] aim "to quantify the amount of preferential attachment that occurs in networks [13, p. 470]." For Flickr, Delicious, LinkedIn and Yahoo Answers they found that preferential attachment "is a reasonable model for edge destination selection [13, p. 465]." Using the statistical method of maximum-likelihood estimation, they show distortions in two assumptions of the preferential-attachment-theory: edge attachment by degree of vertices and edge attachment by the age of a vertex.

D. Small World

According to Watts and Strogatz [26] the connection topology of networks is neither completely regular nor completely random. "But many biological, technological and social networks lie somewhere between these two extremes [26, p. 440]." They are regular networks with increasing amounts of disorders. "We found that these systems can be highly clustered, like regular lattices, yet have small characteristic path lengths, like random graphs. We call them 'small-world' networks, by analogy with the small-world phenomenon… [26, p. 440]." Watts and Strogatz refer to experiments of the social psychologist Stanley Milgram [27] in the 1960s, in which letters passed from person to person were able to reach an individual target in six steps. This was attributed to a few people who have had a lot of connections to other people ("hubs" in modern words) and have been addressed for transmission.

According to Barabási and Bonabeau [24] scale-free networks have also small-world properties. Even a large network with purely randomly placed connections has usually this property [24, p. 68]. If a person has one hundred acquaintances and any of them has again one hundred acquaintances, then 10.000 people are only two handshakes away from this person. And a million people are about three handshakes away [24, p. 68].

Studies have shown that the World Wide Web, scientific collaboration on research papers and general social networks

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have small-world properties [7, p. 32]. Among the 15 most relevant articles small-world properties were found for the OSN Allseron.com [15], Grono.net [15], LastFm [15], Shelfari [15], XFire [15], Flickr [7], YouTube [7], LiveJournal [7] and Orkut [7].

E. Clustering

According to Barabási and Bonabeau [24] the calculation in Section III/D has a hook: It is assumed that the acquaintances do not know each other. "In reality, there is much overlap [24, p. 68]." In fact, already in the second stage fewer than 10.000 people come together. This is because the society "is fragmented into clusters of individuals having similar characteristics (such as income or interests)... [24, p. 68]." Clustering is found in various networks. "At first glance, isolated clusters of highly interconnected nodes appear to run counter to the topology of scale-free networks, in which a number of hubs radiate throughout the system, linking everything. Recently, however, we have shown that the two properties are compatible: a network can be both highly clustered and scale-free when small, tightly interlinked clusters of nodes are connected into larger, less cohesive groups... [24, p. 68]."

Among the 15 most relevant articles the 'clustering coefficient' is introduced as a measure for the cluster. "The *clustering coefficient* of a node with *N* neighbors is defined as the number of directed links that exist between the node's *N* neighbors, divided by the number of possible directed links that could exist between the node's neighbors $(N(N-1))$ [7, p. 39]." Observed clustering coefficients are 0.313 for Flickr, 0.330 for LiveJournal, 0.171 for Orkut and 0.136 for YouTube [7, p. 39]. "The clustering coefficients of social networks are between three and five orders of magnitude larger than their corresponding random graphs. This unusually high clustering coefficient suggests the presence of strong local clustering, and has a natural explanation in social networks: people tend to be introduced to other people via mutual friends, increasing the probability that two friends of a single user are also friends [7, p. 39]."

IV. Criticism on physical theories on OSN

Criticism comes from the sociology. The sociologist Scott states: "Because of an apparent decline in the number of soluble theoretical problems that are left to resolve in their own discipline, a growing number of theoretical physicists have begun to explore the implications of some of their mathematical ideas for the explanation of social and economic phenomena [23, p. 55]." According to Scott, some physicians present their arguments as new - but they are not new at all. "The much-trumpeted innovations that lie at the heart of their 'revolution' - the power law and hubs - are well-known and well-established findings of social network analysts [23, p. 62]." According to the sociologist "it is certainly the case that the terminology of scale-free distribution or power law was not used, but standard frequency distribution tables were used precisely in order to display this pattern [23, p. 60]."

Despite the criticism Scott attests the "new social physics" some good ideas and calls for an interdisciplinary exchange. "Much research in social network analysis has been static and cross-sectional ... This perspective has converged with uses of complexity theory and agent-based computational methods to begin to produce more powerful and productive examinations of longitudinal change [23, p. 64]."

V. Adoption of physical theories on OSN in computer science

This section investigates how physical theories on OSN are picked up by computer scientists. To measure this ACM Digital Library, IEEE Xplore Digital Library and ISI Web of Knowlegde were considered as the most relevant article collections regarding computer science and queried on 10th January 2012. Selection criterion was 'most cited' on IEEE Xplore Digital Library, 'times cited' on ISI Web of Knowlegde and 'citation count' on ACM Digital Library. Searched was in abstract, title and content of articles. Among the results of every searched phrase three articles were randomly chosen and proved that the terms used in the articles were terms in the appropriate sense. The discussion of the results follows in Section V.

Power-law distribution of vertex size: Search terms were "power-law distribution" + "online social network". On ACM Digital Library 912 results were displayed. IEEE Xplore Digital Library showed 3 results, ISI Web of Knowlegde 2. Total number of findings: 964.

Scale-freedom: Search terms were "scale-free" + "online social network". ACM Digital Library displayed 635 results. On IEEE Xplore Digital Library 37 results were shown. ISI Web of Knowlegde revealed 10 results. Total number of findings: 682.

Preferential attachment: Search terms were "preferential attachment" + "online social network". On ACM Digital Library 316 results were displayed. IEEE Xplore Digital Library showed 40 results, ISI Web of Knowlegde 5. Total number of findings: 361.

Small World: Search terms were "small world" + "online social network". ACM Digital Library displayed 14.874 results. On IEEE Xplore Digital Library results 784 results were shown. ISI Web of Knowlegde revealed 21 results. Total number of findings: 15.679.

Clustering: Search terms were "cluster" + "online social network". On ACM Digital Library 6.393 results were displayed. IEEE Xplore Digital Library showed 3.614, ISI Web of Knowlegde 57 results. Total number of findings: 10.064.

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VI. Conclusion

In this paper, we studied OSN, seen through the glasses of the physical approach of a "new science of networks". Some physical theories of the evolution of OSN are widely discussed among computer scientists: small world effect, clustering, power-law distribution of vertex size and scale-freedom. On the contrary, only very few publications of computer scientists deal with preferential attachment on OSN. Hence this topic was identified as a future research gap.

A. Future research gap: Preferential attachment on OSN

Physical theories on OSN are already picked up by computer science – but to varying degrees. Most discussed is the small world effect on OSN (15.679 results). Even the phenomenon of clustering on OSN (10.064 results) and the power-law distribution of vertex size in connection with OSN (964 results) attracts a lot of publications in computer science. Fewer articles deal with the scale-freedom of OSN (682 results). Surprisingly few articles have been published to the topic preferential attachment on OSN: 361 results. These are only 2.30 percent of the number of articles published to the small world effect on OSN – the number of published articles is out of proportion to the importance of the topic. According to Barabási and Bonabeau the process of preferential attachment occurs anywhere [24, p. 64]. "Likewise, the most relevant articles in the scientific literature stimulate even more researchers to read and cite them, a phenomenon that noted sociologist Robert K. Merton called the Matthew effect, after a passage in a Christian gospel: "For unto every one that hath shall be given, and he shall have abundance [24, p. 65]." In other areas – like the Internet and the U.S. biotech industry – preferential attachment has already been explored [24, p. 65]. Open questions, occurring through the identified research gap, are listed in Section V/C.

B. Limitations

A shortcoming of this paper is that the social networks, described in the 15 most relevant articles, are not homogeneous. Only a few are OSN in the sense of definition in Section II, for instance grono.net [15] or Wealink [11]. This applies to the database queries: During the calculation of the total number of results was not differentiated between OSN in the strict sense of definition in Section II and in a broader sense.

Another shortcoming lies in the lack of empirical studies among the 15 most relevant articles on the evolution of MySpace and Facebook, currently the largest OSN. To prove this, ACM Digital Library, IEEE Xplore Digital Library and ISI Web of Knowledge were queried on 26th January 2012. Search terms were 'Facebook', 'MySpace', 'social network' and 'evolution'. Selection criterion was 'most cited' on IEEE Xplore Digital Library, 'times cited' on ISI Web of Knowlegde and 'citation count' on ACM Digital Library. Searched was in abstract, title and content of articles. In the case of Facebook the query revealed 1261 results, in the case of MySpace 596 results. In both cases, the abstracts of the first 50 results of ACM Digital Library were checked, and even the abstracts of all results of IEEE Xplore Digital Library and ISI Web of Knowlegde. Articles that deal explicitly with the evolution of Facebook and MySpace were not found. There were, however, founded articles that already belong to the fundus of the 15 most relevant articles, for instance [7], [18] and [28].

According to Ellison et al. much of the existing academic research on Facebook has focused on identity presentation and privacy concerns [4]. Ryan und Xenos accentuate: "Despite the potential implications of Facebook use, there is a distinct lack of empirically derived theory in this area [6, p. 1658]." This could be, because Facebook is a relatively recent phenomenon, and as such, there has been limited opportunity for exploratory research [6].

C. Open Issues

The exploration of preferential attachment on OSN opens up a series of research questions for computer scientists. How is this process structured on OSN? How do the running of this process on OSN differ from the running in the offline world? How does the preferential attachment influence the dynamics of the evolution of OSN? What does preferential attachment for designing and conducting of OSN mean? How could a theory of preferential attachment be used to improve current OSN and to design new applications for OSN? How does preferential attachment influence the stability of OSN? Is it possible, to transfer the findings on preferential attachment, which have been obtained through the OSN, in the offline world?

Not only the "new science"-model, which was presented in this paper, uses preferential attachment, also other mechanisms do [28, p. 843]. "The transitive linking model..., which is based on continuously completing triangles with only an edge missing, is one such example [28, p. 843]." Another point of view is a fitness-based approach. "In any fitness-based approach, each node has its own fitness value and they are linked by the function of their fitness values [28, p. 843]." Hence further research could be done by computer scientists to compare and to integrate these different approaches and, if possible, to apply the integrated approach on OSN.

It could also stimulate research to include the perspectives of other sciences. OSN had attracted scientists of different backgrounds – at this point mostly physicists and computer scientists [11, p. 1110]. "However the main body in the virtual world is still persons in real world, thus as pointed out by Tim Berners-Lee – the "father of the World Wide Web", understanding the web community may also require insights from sociology and psychology every bit as much as from physics and computer science... [11, p. 1110]."

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