

# Effect of citation patterns on network structure

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## Abstract

We propose a model for an evolving citation network that incorporates the citation pattern followed in a particular discipline. We define the citation pattern in a discipline by three factors. The average number of references per article, the probability of citing an article based on its age and the number of citations it already has. We also consider the average number of articles published per year in the discipline. We propose that the probability of citing an article based on its age can be modeled by a *lifetime distribution*. The lifetime distribution models the citation lifetime of an average article in a particular discipline. We find that the citation lifetime distribution in a particular discipline predicts the topological structure of the citation network in that discipline. We show that the power law exponent depends on the three factors that define the citation pattern. Finally we fit the data from the Physical Review D journal to obtain the citation pattern and calculate the total degree distribution for the citation network.

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## I. INTRODUCTION

Citation networks of scholarly publications have generated considerable interest in recent times. In citation networks, the articles are the nodes and an edge is attached between two nodes when one article cites another. Similar to other networks, such as the telecommunication network, social networks, neural networks etc., citation networks were also observed to have a scale free structure [1]. The first study of citation statistics was made by de Solla Price [1] who proposed that the rate at which an article gets cited is proportional to the number of citations it already has. His model was based on the models by Yule [2] and Simon [3]. Later, a simple analytical model which leads to a scale free structure in growing networks was proposed by Barabási and Albert [4]. The Barabási- Albert (BA) model introduced a similar concept called *preferential attachment* whereby a new node is connected to some old node in the network based on its number of edges. This leads to the scale free structure in most networks. In all these models, an older node with a large number of edges will go on accumulating new edges irrespective of its age. However, citation networks obtained from real world datasets do not follow a simple scaling solution. Though people tend to cite highly cited papers, old papers are rarely cited, especially if the research described in them have already been incorporated in recent text books. This lead to modifications to the BA model where the attachment probability depended on the number of edges of the node and was also proportional to some power of the age of the node [6].

Lehmann et. al. [7] found that though the citation network in the SPIRES database could be described by simple power laws, the exponent of the power law changed when the number of citations exceeded a certain value. The data thus suggested that the citation distribution is described by two independent power laws in two different domains. The data could also be fitted with a stretched exponential. They developed a model [8] where some nodes are considered dead after sometime and are not able to acquire new links in the growing network. Their model successfully explained the results from the SPIRES database. Similarly Chun et. al. [9] who studied the citation network in the journal Scientometrics, found that the out-degree in the citation network could be fitted by two independent power laws whereas the in-degree could be fitted with a single power law. Vazquez [10] did a detailed study of the out-degree distribution of citation networks from various journals. He found that there was a difference in the citation distribution for journals which have a restriction in the

number of pages per article. He proposed a recursive search model which partially explained some of the features observed in various citation networks. Börner et al.[11] proposed the TARL (Topics, Aging, Recursive Linking) model, which is a general process model that models the growth of a bipartite network of authors and articles. They used a 20 year data set of articles published in the Proceedings of the National Academy of Sciences (*PNAS*) to validate their model. The deviations from power law in the citation distribution observed for the PNAS data set could be explained by their model. In the TARL model, the probability of highly cited papers garnering more citations is offset by incorporating a bias to cite more recent papers. The number of citations received as a function of age was fitted by a Weibull distribution. The scale parameter of the Weibull distribution represented the aging bias.

Apart from these models that explained the scaling co-efficients of specific data sets, there were other general analytical models where the attachment probability depended exponentially on the age of the node [12, 13]. These studies demonstrated that the introduction of aging significantly transformed the statistical properties of the growing network [13]. In this work, we aim to understand the underlying reasons that govern the power law behavior and scaling co-efficients of various citation networks. We propose a general analytical model that incorporates the citation pattern in a particular discipline to predict the topological structure of the final network. Citation patterns in different disciplines are not always well defined. To obtain quantitative estimates we define the citation pattern in a particular discipline by the following factors, (i) the average number of references per article, (ii) the citation probability based on age and (iii) the citation probability based on the number of citations it already has. In addition, we also consider the average number of articles published in that discipline per year. Our citation probability depends on age and previous number of citations. These two probabilities are assumed to be independent of each other. We use the master equation approach and solve the difference-differential equation to obtain the probability of a node to have  $k$  number of citations at time  $t$ . Finally, the degree distribution is obtained by summing over all the nodes in the network at a particular time.

The probability of citing an article based on the number of citations it already has, is modeled by the preferential attachment method proposed by Barabási and Albert [4]. We propose that the probability of citing an article based on its age can be modeled by a lifetime distribution. Lifetime distributions like the Weibull and the lognormal have been used extensively for life data analysis in predicting the mean life for a wide array of complex

machinery and other products for everyday use. They have been used to model the lifetime of organisms in an ecosystem, here we use them to model the citation lifetime of an article in a particular discipline. Citation lifetime is given by the distribution of citations over time [5]. A high citation lifetime indicates that articles are being cited over a longer period of time. The other reason for using lifetime distributions is that they are very versatile and can take on the characteristics of other types of distributions based on the value of their parameters (e.g. the Weibull gives the exponential distribution for a shape parameter of 1). We find that the probability of a node to have  $k$  number of citations at time  $t$  depends on the parameters of the chosen distribution. For certain parameters it is possible to obtain a power law distribution while for others it is more like a stretched exponential. Since the parameters of the chosen distribution themselves depend on the citation pattern in that particular discipline, we conclude that it is the citation pattern in a particular discipline which plays a significant role in the degree distribution of a citation network. Our results show that the scaling exponents of the final degree distribution depends significantly on the citation pattern.

## II. OUR MODEL

As we are dealing with a citation network here, the nodes of the network are the articles that are published. So nodes and articles refer to the same object in our model. Like previous models [12, 13] we consider preferential attachment and aging to be independent of each other. So the total attachment probability in our model depends on the degree of a particular node  $k$  and its age  $(t - t_0)$  where  $t$  is the present time and  $t_0$  is the time it entered the growing network. We assign an initial degree  $k_0$  to each node.  $k$  is the total degree of a particular node, so its out-degree is  $k_0$  and in-degree is  $(k - k_0)$ . For the time being however, we do not make a distinction between incoming and outgoing degree distribution. Our time unit here is in years and  $m$  number of nodes enter the network at each timestep. The probability  $p(k, t - t_0)$  that a node (which had entered the network at time  $t_0$ ) will have a degree  $k$  at time  $t$  is given by,

$$p(k, t - t_0) = f(t - t_0) \left[ \frac{k - 1}{2t} p(k - 1, t - t_0 - 1) - \left(1 - \frac{k}{2t}\right) p(k, t - t_0 - 1) \right] \quad (1)$$

where  $f(t - t_0)$  is a lifetime distribution which satisfies the condition  $f(t - t_0) = 0$  at  $t = t_0$ .

The master equation obtained from Eq. 1 is given by,

$$\left[ \frac{2t}{f(t-t_0)} \right] [p(k, t-t_0+1) - p(k, t-t_0)] = (k-1)p(k-1, t-t_0) - kp(k, t-t_0). \quad (2)$$

We do a standard Z-transform,

$$\Phi(z, t-t_0) = \sum p(k, t-t_0)z^{-k} \quad (3)$$

and obtain,

$$\left[ \frac{2t}{f(t-t_0)} \right] \frac{d\Phi}{dt} = (z-1) \frac{d\Phi}{dz} \quad (4)$$

This is subject to the condition at  $t = t_0$ ,

$$\Phi(z, 0) = mz^{-k_0}, \quad (5)$$

where  $m$  is the average number of articles published in that discipline per year and  $k_0$  is the average number of references an article has. The other condition is,

$$\Phi(1, t-t_0) = 1. \quad (6)$$

Eq. 4 is solved using the above conditions and the final solution is given by,

$$p(k, t-t_0) = \frac{(k_0+k-1)!}{(k_0-1)!k!} (-1)^k m \left[ (\exp(-g(t-t_0)) - 1)^k \right] [\exp(-k_0g(t-t_0))] \quad (7)$$

where  $g(t-t_0) = \int \frac{f(t-t_0)dt}{2t}$ . If  $f(t-t_0)$  is the Weibull distribution, it is possible to solve this integral analytically using special functions. The final answer is a non-trivial combination of the error function and the exponential integral. Since we are dealing with finite time periods, we choose to solve the integral numerically.

In the next section, we obtain the total degree distribution for two different distributions, the Weibull distribution and the lognormal distribution. The two-parameter Weibull and the lognormal distribution are characterized by the shape parameter  $a$ , and the scale parameter  $b$ . We impose the condition  $f(t-t_0)$  is zero at  $t = t_0$ . For a given dataset, we can fit the data and obtain the two parameters but for our analysis we consider the shape parameters to be constant and vary only the scale parameters. The effect of the scale parameter is to stretch the distribution. Since the distribution is over age here, increasing the scale parameter means citing relatively older papers.

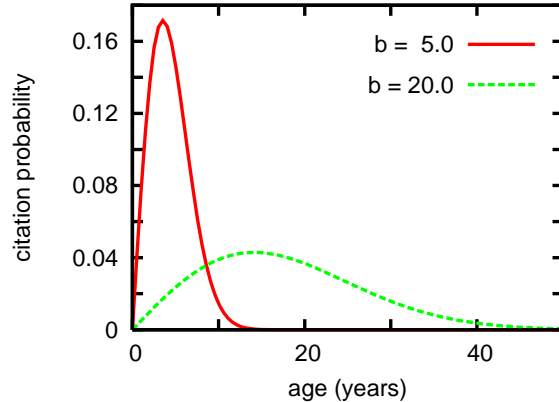


FIG. 1:

Citation lifetime distribution of an article for the Weibull distribution. The solid (red) line is for  $b = 5$  and the dashed (green) line is for  $b = 20$ .

### III. RESULTS

Apart from the parameters characterizing the probability of citing articles based on their age, we also have two other inputs, the average number of papers published each year  $m$ , and the average number of references  $k_0$  each paper has. Initially we keep these two factors constant and investigate the effect of the citation distribution on the total degree distribution. We consider  $m = 200$  and  $k_0 = 20$  and the time period is 50 years.

#### A. Weibull distribution

We consider the two parameter Weibull distribution given by,

$$f(t - t_0) = ab^{-a}(t - t_0)^{(a-1)} \exp(-((t - t_0)/b)^a) \quad (8)$$

The shape parameter  $a = 2$  satisfies our initial condition. The scale parameter is varied to study how the distribution pattern affects the final structure of the network.

Fig. 1 gives the citation lifetime distribution of an article for the Weibull distribution. The x-axis is the age of the article and the y-axis gives it's probability of citation. The solid (red) line is for scale parameter  $b = 5$  and the dashed (green) line is for  $b = 20$ .  $b = 20$  means that the discipline tends to cite relatively older articles while  $b = 5$  indicates that recent articles are more likely to be cited.

We obtain the total degree distribution for the two scale parameters in Fig. 2 For

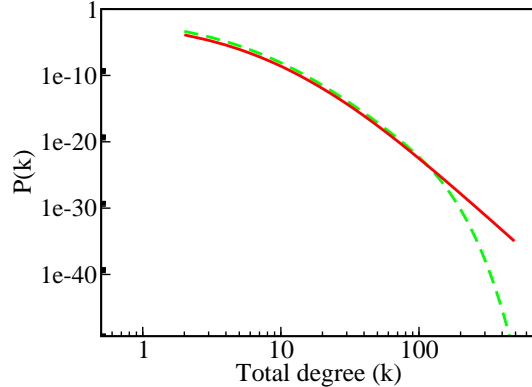


FIG. 2:

Degree distribution of citations to an article for different values of the scale parameter in the Weibull distribution. The solid (red) line is for  $b = 5$  and the dashed (green) line is for  $b = 20$ .

the Weibull function the tail of the degree distribution changes when the citation pattern changes. We do not get a simple power law in any of the cases. However, for  $b = 5$ , it is possible to fit the final degree distribution using two power laws. This implies that in disciplines where more recent articles are likely to be cited, the total degree distribution can be described by two power laws with different coefficients.

## B. Lognormal distribution

The other commonly used lifetime distribution is the lognormal distribution given by,

$$f(t - t_0) = \frac{\exp((-\ln(t - t_0) - b)^2/2a^2)}{(t - t_0)a\sqrt{\pi}}. \quad (9)$$

This satisfies our boundary condition for  $a = 0.5$ . The scale parameter here is taken to  $b = 1.5$  and  $b = 3.0$ .

Fig. 3 gives the citation lifetime distribution of an article for the lognormal distribution. The x-axis is the age of the article and the y-axis gives it's probability of citation. The solid (red) line is for scale parameter  $b = 1.5$  and the dashed (green) line is for  $b = 3.0$ . Again,  $b = 3.0$  means that the discipline tends to cite older articles while  $b = 1.5$  indicates that recent articles are more likely to be cited. The distributions are similar with some minor differences. The rising of the curves are different. So the number of citations that articles accumulate in the initial years after publication determine whether the citation lifetime can

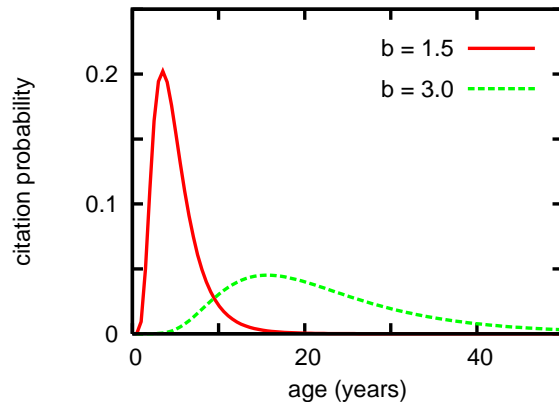


FIG. 3:

Citation lifetime distribution of an article for the lognormal distribution. The solid (red) line is for  $b = 1.5$  and the dashed (green) line is for  $b = 3.0$ .

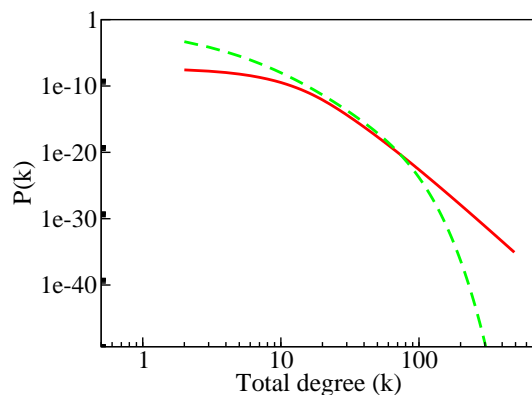


FIG. 4:

Degree distribution of citations to an article for different values of the scale parameter for the lognormal distribution. The solid (red) line is for  $b = 1.5$  and the dashed (green) line is for  $b = 3.0$ .

be described by a Weibull or a lognormal distribution.

Fig. 4 gives the total degree distribution for the lognormal distribution. As expected, it is similar to the one obtained for the Weibull. However, unlike the Weibull, here there are differences both in the initial and the tail part for the different scale parameters. The Weibull distribution with  $b = 20$  and the lognormal distribution with  $b = 3.0$  gives similar degree distributions. It is when  $b$  is small, we see that the total degree distribution changes depending on the kind of lifetime distribution considered. This implies that if the average



citation age of an article in a discipline is small, the number of citations received in the initial years after publication are important to determine the structure of the citation network in that discipline.

We have thus verified that citing patterns do indeed affect the final degree distribution of the network. The two lifetime distributions that we have chosen reflect the citation patterns in different disciplines. The two distributions differ in the rise of the citation probability with age. Though the scale parameter stretches both the distributions, for the lognormal distribution, the number of years before an article actually gets cited also changes. This changes the total number of citations accumulated in the initial years. The parameters of either of these distributions can be chosen to obtain a heavy tailed distribution. The scale parameter in that case would be small. Since the structure of the citation network depends on the parameters of the distribution, we conclude that the average age of citations in a discipline, the number of citations accumulated in the recent years and the tendency to cite more recent articles affect the topology of the citation network.

### C. Number of articles and references

Next we consider the average number of articles published each year and study how the increase in publications can affect the total degree distribution of the network. Increasing the number of articles and increasing the time are similar since the average number of articles published each year in a discipline is considered constant. We find that increasing  $m$  does not change the topology of the network. It only changes the numerical values obtained in the final degree distribution. The number of references cited by each article on the other hand does affect the topological structure of the network. This is particularly relevant as the number of references in different disciplines may vary considerably. The citation distribution is taken to be a Weibull distribution with the shape parameter 2 and the scale parameter  $b = 5$ . The number of references  $k_0$  considered are 20, 40, 80, and 120. Though review articles can have a much larger number of references, we consider the maximum value of 120 since the number of articles generated per year in our case is kept constant at 200.

Fig. 5 gives the total degree distribution for different values of  $k_0$ . We find that a change in the number of references affects the network structure. For smaller number of references the degree distribution can be described by a stretched exponential. As the average number

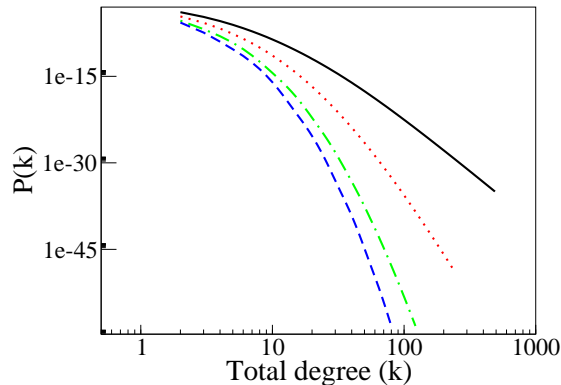


FIG. 5:

Total degree distribution for a Weibull distribution with  $a = 2$  and  $b = 5$  when the number of references vary. The straight (black) line corresponds to  $k_0 = 20$ , the dotted (red) line to  $k_0 = 40$ , the dot-dash (green) line to  $k_0 = 80$  and the dashed (blue) line to  $k_0 = 120$ .

of references increase, the distribution becomes exponential in nature (dashed curve in Fig. 5). Similar results are obtained for  $b = 20$  and for the lognormal distribution. These indicate that the citation networks of two disciplines which have different citation practices will have different topological structure. The discipline which has a larger number of references per article will have deviations from the scale free structure and the total degree distribution will be given by an exponential instead of a power law.

#### IV. REAL-WORLD CITATION DISTRIBUTIONS

We now discuss how our model relates to the various results obtained previously from different data sets. For a finite time period, we have identified three major parameters which determine the citation pattern in a discipline. These are (i) the number of references per article (ii) the average age at which articles get their maximum citations and (iii) the rate at which the article accumulates citations in the initial years after publication. This rate is given by the rise in the citation lifetime curve and determines which distribution would be a better fit to the discipline. The study of the citation network of the Scientometric journal [9] over a 26 year time period generates two power laws with different scaling coefficients. As the authors point out, the number of articles published each year is relatively constant

over this period. So the deviations here are mostly due to the difference in the number of references per article. They also find that the journal had a large number of self-referencing in the first year. This went down steeply immediately after the first year and then increased steadily over time in the next 25 years. According to our model, as the number of references per article increases, the slope of the degree distribution on a logarithmic scale becomes steeper. So the change in the power law coefficient in the degree distribution could be due to the increase in the number of references within the journal. Results obtained from the SPIRES database [7] also show that the degree distribution in high energy physics can be fitted by two power laws independent of each other. As mentioned previously, the total degree distribution obtained from the Weibull distribution with shape parameter  $a = 2$  and scale parameter  $b = 5$  can also be fitted by two power laws independent of each other.

These values of the parameters are not unique, other combinations also generate similar curves but with different scaling coefficients. So it may well be that the citation pattern in each of these datasets are fit with a Weibull or lognormal distribution with different parameters. Our motivation for using lifetime distributions to illustrate the importance of citation pattern on network evolution is largely theoretical. For a better validation of the model it is necessary to obtain the distribution from an actual dataset and fit a probability distribution. The parameters obtained from the fit can then be used to predict the degree distribution of the final network. We do this for citations obtained from the Physical Review D journal.

The degree distribution of the citation network for the Physical Review D journal has previously been analyzed extensively [10, 14, 15]. However the citation pattern has not been obtained before. We obtain the citation pattern by plotting the number of citations received by an article against the age of the article. This data is then normalized and fitted with a probability distribution. Fig. 6 gives the plot. The probability distribution turns out to be a lognormal distribution with the parameters  $a = 1.1$  and  $b = 1.7$ .

Once  $f(t - t_0)$  is obtained, we calculate the citation probability from Eq. 7. We plot this in Fig. 7. Since we are considering references in Physical Review D journals only, we take the average number of articles published per year to be 1000. The Physical Review D started in 1970. In the initial years of publication, the average number of articles was very low (about 300) but in recent years the number has increased to around 2000. Since our average number of articles generated each year remains constant throughout the time period

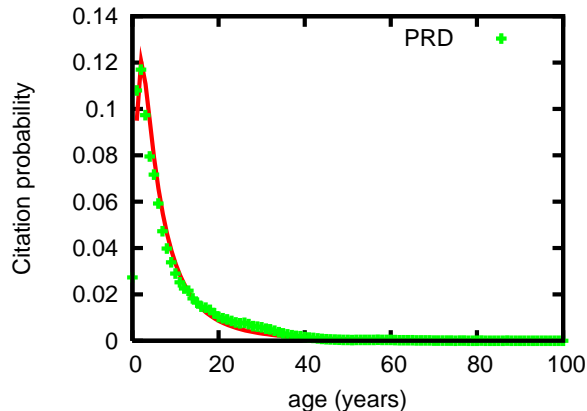


FIG. 6:

The citation pattern in the Physical Review D journal is fitted with a lognormal distribution with

$$a = 1.1 \text{ and } b = 1.7$$

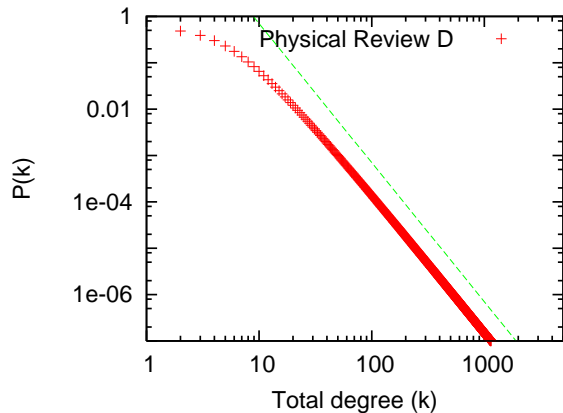


FIG. 7:

Degree distribution obtained from Eq. 7 for Physical Review D. The number of articles per year is 1000 and the average number of references is 4. The line denoting the power law is shifted upwards for better visualization of the data and the fit.

considered (1970 - 2004), we take  $m = 1000$ . To obtain a scaling co-efficient of  $-3$  in the tail region (as obtained in Ref.[14]) with  $m = 1000$ , we find that the number of references should be 4. The total degree distribution and the power law with an exponent of  $-3.0$  is shown in Fig. 7.

Since an average number of references of 4 seemed quite small, we went back to the dataset and examined the references in the journal Physical Review D. A random sampling indicated that the initial articles in the journal have few or no citations. Later articles have an average of 20 references per article but most of the articles cited are published in other journals. The

average number of references to Physical review D is less than 10. The citation lifetime was obtained from the references from articles published in the Physical Review D irrespective of where the *cited* article was published. However, the degree distribution in Ref.[14] did not include citations to articles outside the Physical Review journals. So the average number of references does not seem anomalous. It is the average number of references to Physical Review journals in Physical Review D. Since many of the initial articles in the journal had references to journals cited outside the Physical Review, the average number of references in the total time period is reduced.

In our model we have considered the number of articles published and the average number of references per article to be constant throughout the time period. This is not true for real world citation data. We have shown that changing the number of references changes the scaling coefficient, since in the real world data set these number keep changing, it becomes difficult to fit any citation data with an unique power law. This is further illustrated in Lehmann's work [7], where he plots the degree distribution for the total SLAC SPIRES database and also plots the degree distribution separately for the subfields in the database. The citation pattern in the subfields being more homogeneous, the degree distribution here can be fit by two power laws whereas the degree distribution for the entire database can be fit by multiple power laws.

## V. SUMMARY AND CONCLUSIONS

We have presented an analytical model for an evolving citation network that takes into account the citation pattern in a particular discipline. Though earlier models have considered the aging of articles and preferential attachment, our model is the first to include definite characteristics that define the citation pattern in a discipline. Apart from the citation pattern, we also include the number of articles published per year. We find that all these together determine the total degree distribution of the network.

We propose modeling the aging probability by a lifetime distribution. Two of the most commonly used lifetime distributions are the Weibull and the lognormal. The Weibull distribution has been used previously in the TARL model [11]. It was used to model the aging characteristics of the citation network obtained from the PNAS dataset. We also found that the aging characteristics of the citation network in the Physical Review dataset fits a

lognormal distribution. The choice of lifetime distributions to model the aging probability is thus consistent with real datasets.

We find that the topological structure of the network depends on the citation practices followed in different disciplines. Citation practices vary considerably between different disciplines. The average age of the cited article and the number of references per article seem to be the two most important factors which determine the scaling coefficient of the power law. We find that the deviations from the power law structure are due to aging and the number of references per article. We use the Physical Review D dataset to validate our model. We consider an average of 1000 articles published in a year. A power law with exponent  $-3$  is obtained for an average of 4 references per article. The low number of references is not altogether anomalous because it refers to the average number of reference to Physical Review journals only. However, there are many assumptions in the model which may have lead to this value. We now discuss these assumptions and discuss their impact on our model.

The probability of citation based on preferential attachment and aging are considered to be independent of each other. Though this is an accepted assumption in modeling citation networks, it is not true in the real world [15]. Highly cited articles will definitely have a longer lifetime compared to the less cited articles in any discipline. In Ref. [15] the average citation age for most Physical Review papers is found to be 6.2 years, while the average citation age for highly cited papers is found to be 11.7 years. This means that the two probabilities should be dependent on each other, even if the dependency is small. Since the total degree distribution of our model depends on the citation pattern, a change in the citation pattern will definitely change the final structure of the network.

We have also assumed that the number of articles published each year and the number of references per article are constant. For real world citation data neither is true. In fact in some cases the increase in the number of articles published each year is exponential. This is especially true for the Physical Review D journal which we have used to validate our model. As mentioned previously, the number of articles published each year in this journal has grown by an order of magnitude in three decades. This unfortunately is not reflected in our model which considers an average value for the whole time period. However, our point was to exemplify the importance of citation patterns in the evolution of a citation network. It is encouraging to find that our final degree distribution is similar to the degree distribution obtained in ref.[14]. While our model is able to explain the differences observed in differ-

ent citation networks qualitatively, we hope to improve it further and make quantitative predictions about citation patterns observed in different disciplines.

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