Prediction of highly cited papers

M. E. J. Newman

Department of Physics and Center for the Study of Complex Systems, University of Michigan
Ann Arbor, MI 48109, USA

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Abstract – In an article in the pages of this journal five years ago, we described a method for predicting which scientific papers will be highly cited in the future, even if they are currently not highly cited. Applying the method to real citation data we made predictions about papers we believed would end up being well cited. Here we revisit those predictions, five years on, to see how well we did. Among the over 2000 papers in our original data set, we examine the fifty that, by the measures of our previous study, were predicted to do best and we find that they have indeed received substantially more citations in the intervening years than other papers, even after controlling for the number of prior citations. On average these top fifty papers have received 23 times as many citations in the last five years as the average paper in the data set as a whole, and 15 times as many as the average paper in a randomly drawn control group that started out with the same number of citations. Applying our prediction technique to current data, we also make new predictions of papers that we believe will be well cited in the next few years.

Introduction. – Citations of scientific papers are considered to be an indicator of papers’ importance and relevance, and a simple count of the number of citations a paper receives is often used as a gauge of its impact. However, it is also widely believed that citations are affected by factors besides pure scientific content, including the journal a paper appears in, author name recognition, and social effects [1,2]. One substantial and well-documented effect is the so-called cumulative advantage or preferential attachment bias, under which papers that have received many citations in the past are expected to receive more in the future, independent of content. A simple mathematical model of this effect was proposed by Price [3], building on earlier work by Yule [4] and Simon [5], in which paper content is ignored completely and citation is determined solely by preferential attachment plus stochastic effects. Within this model, the expected number of citations a paper receives is a function only of its date of publication, measured from the start of the topic or body of literature in which the paper falls, and shows a strong “first-mover effect” under which the first-published papers are expected to receive many more citations on average than those that come after them. Indeed the variation in citation number as a function of publication date is normally far wider than the stochastic variation among papers published at the same time. In a previous paper [6] we compared the predictions of Price’s model against citation data for papers from several fields and found good agreement in some, though not all, cases. This suggests that pure citation numbers may not be a good indicator of paper impact, since much of their variation can be predicted from publication dates, without reference to paper content.

Instead, therefore, we proposed an alternative measure of impact. We proposed that rather than looking for papers with high total citation counts, we should look for papers with counts higher than expected given their date of publication. Since publication date is measured from the start of a field or topic, and since different topics have different start dates, one should only use this method to compare papers within topics. The appropriate calculation is to count the citations a paper has received and compare that figure to the counts for other papers on the same topic that were published around the same time. In our work we used a simple z-score to perform the comparison: we calculate the mean number of citations and its standard deviation for papers published in a window close to the date of a paper of interest, then calculate the number of standard deviations by which that paper’s citation
count differs from the mean. Papers with high $z$-scores we conjecture to be of particular interest within the field.

One promising feature of this approach is that the papers it highlights are not necessarily those with the largest numbers of citations. The most highly cited papers are almost always the earliest in a field, in part because of the first-mover effect but also because they have had longer to accumulate citations. More recent papers usually have fewer citations, but they may still have high $z$-scores if the count of their citations significantly exceeds the average among their peers. Thus, the method allows us to identify papers that may not yet have received much attention but will do so (we conjecture) in the future.

In our previous study, we used this method to identify some specific papers that we believed would later turn out to have high impact. Here we revisit those predictions to see whether the papers identified have indeed been successful. To quantify success, we look again at citation counts, and to minimize the preferential attachment bias we compare them against randomly drawn control groups of papers that had the same numbers of citations at the time of the original study. As we show, our predictions appear to be borne out: the papers previously identified as potential future successes have received substantially more attention than their peers over the intervening years.

**Previous results.** – In this section we briefly review some of the results from our previous paper [6], which we will refer to as Paper 1.

In Paper 1 we examined citation data from several different fields in physics and biology, but made specific predictions for one field in particular, the field of interdisciplinary physics known as network science. This field is an attractive one for study because it has a clear beginning—a clear date before which there was essentially no published work on the topic within the physics literature (although there was plenty of work in other fields)—and a clear beginning is crucial for the theory developed in the paper to be correct and applicable. (It is also the present author’s primary field of research, which was another reason for choosing it.) It is again on papers within network science that we focus here.

In Paper 1 we assembled a data set of 2407 papers on network science published over a ten year period, starting with the recognized first publications in 1998 and continuing until 2008. The data set consisted of papers in physics and related areas that cited one or more of five highly cited early works in the field [7–11], but excluding review articles and book chapters (for which citation patterns are distinctly different from those of research articles). We then calculated the mean and standard deviation of the number of citations received by those papers as a function of their time of publication. Crucially, however, our theoretical studies indicate that “time” in this context is most correctly defined not in terms of real time, but in terms of number of papers published within the field. If $n = 2407$ in this case), then the “time” $t$ of publication of the $i$-th paper is defined to be $t = i/n$, where papers are numbered in the order of their publication. Thus, $t$ runs from a lowest value of 1/n for the first paper in the field to 1 for the most recent paper. It is in terms of this variable that we perform our averages.

Armed with these results, we then calculate a $z$-score for each paper as described in the introduction; we take the count of citations received by a paper, subtract the mean for papers published around the same time, and divide by the standard deviation. Figure 1 reproduces a plot from Paper 1 of $z$-scores for papers in the data set. Only $z$-scores that exceed 2 are shown, since these are the ones we are most interested in, corresponding to papers whose citation counts are significantly above the mean for their peers. As the figure shows, there are within this set a small number of papers that stand out as having particularly high $z$-scores. Our suggestion was that these were papers to watch, that even if they did not currently have a large number of citations, they would in future attract significant attention. Table 1 lists twenty of the top papers by this measure from our 2008 data set along with their citation counts and $z$-scores.

Five years have elapsed since Paper 1 was written, giving us five years of additional citation data for the same papers. In the following section we look more closely at the papers in table 1 and other top papers and show that, while there is plenty of variation in the fortunes of

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1 The averages for the network science data were calculated by histogramming the data in bins of 120 papers each, meaning there were about 20 bins over the entire time interval spanned by the data. The same bins were also used for calculating the standard deviations. For the data on strange matter, bins of 60 papers each were used (a smaller figure because the data set is proportionately smaller). More details of the methodology can be found in [6].

2 We have been slightly selective about the papers listed in table 1. The actual top twenty papers included three written by the present author, two of which [12,13] we omitted from the list out of modesty. The table lists the twenty papers with the highest $z$-scores among those that remain. Similarly, two of the author’s papers [14,15], have been omitted from table 2.
Table 1: Twenty of the papers in network science with the highest $z$-scores in 2008, as calculated using the method described in the text, listed in chronological order along with their citation counts both now and at the time of the previous study.

| Year | Author(s) | Reference | 2008 cites | 2013 cites | $z$-score |
|------|-----------|-----------|------------|------------|----------|
| 1998 | Watts D. J. and Strogatz S. H. | Nature **393**, 440 | 7807 | 7807 | 6.384 |
| 1999 | Barabási A.-L. and Albert R. | Science **286**, 509 | 7955 | 7955 | 6.713 |
| 2002 | Milo R. et al. | Science **298**, 824 | 1775 | 1775 | 5.964 |
| 2002 | Ravasz E. et al. | Science **297**, 1551 | 1343 | 1343 | 5.358 |
| 2004 | Barrat A. et al. | Proc. Natl. Acad. Sci. U.S.A. **101**, 3747 | 760 | 760 | 5.798 |
| 2005 | Guimerà R. and Amaral L. A. N. | Nature **433**, 895 | 677 | 677 | 5.266 |
| 2005 | Palla G. et al. | Nature **435**, 814 | 902 | 902 | 7.047 |
| 2005 | Santos F. C. and Pacheco J. M. | Phys. Rev. Lett. **95**, 098104 | 621 | 621 | 6.216 |
| 2006 | Newman M. E. J. | Proc. Natl. Acad. Sci. U.S.A. **103**, 8577 | 901 | 901 | 8.954 |
| 2006 | Ohtsuki H. et al. | Nature **441**, 502 | 437 | 437 | 6.614 |
| 2006 | Zhou C. S. et al. | Phys. Rev. Lett. **96**, 034101 | 647 | 647 | 6.475 |
| 2006 | Kim P. M. et al. | Science **314**, 1938 | 222 | 222 | 6.109 |
| 2007 | Dosenbach N. U. F. et al. | Proc. Natl. Acad. Sci. U.S.A. **104**, 11073 | 371 | 371 | 7.214 |
| 2007 | Palla G. et al. | Nature **435**, 814 | 281 | 281 | 5.386 |
| 2007 | Tadić B. et al. | Int. J. Bifurcat. Chaos **17**, 2363 | 58 | 58 | 5.488 |
| 2008 | Perc M. and Szolnoki A. | Phys. Rev. E **77**, 011904 | 129 | 129 | 6.019 |
| 2008 | Kozma B. and Barrat A. | Phys. Rev. E **77**, 016102 | 69 | 69 | 6.019 |
| 2008 | Hidalgo C. A. and Rodriguez-Sickert C. | Physica A **387**, 3017 | 29 | 29 | 6.245 |
| 2008 | Clauset A. et al. | Nature **453**, 98 | 255 | 255 | 6.245 |
| 2008 | Estrada E. and Hatano N. | Phys. Rev. E **77**, 036111 | 47 | 47 | 6.245 |

individual papers, these papers have clearly done better on average than their peers in the intervening time.

**New results.** – To quantify the success (or lack of success) of the papers identified by high $z$-scores in our 2008 study, we once more turn to the citation record. Duplicating our earlier methodology, we have again assembled a set of papers citing the same five early works in the field but excluding reviews and book chapters. Where the data of Paper 1 covered only a ten year period, however, our new data cover an additional five years for a total of fifteen years from 1998 to 2013. The new data set contains 6976 papers in total, over twice as many as we found in 2008. Indeed the first and most obvious conclusion from the new data is that the field of network science has grown tremendously in the last five years. Figure 2 shows a plot of the number of papers in the data set by year of publication, and the rapid growth is immediately apparent. In the first year of the data set, the year 1998, there was only one paper. In 1999 there were 14. In 2012, the last full year represented, there were 895 papers. Despite this growth, however, and despite the fact that 2012 produced a bumper crop of papers, one might tentatively say from the figure that the field has plateaued — the vigorous growth of the first decade appears roughly to have leveled off around 800 papers per year after about 2008.

Using our new data set we have located each of the 2407 papers studied in Paper 1 and determined how many citations, in total, they had received as of August 2013, approximately five years after the study of Paper 1. For the selection of papers in table 1 these figures are given in the second-to-last column of the table. From them we can calculate the gain in citations received by each paper. As the table shows there is plenty of variation, but all the papers, without exception, have significantly more citations than they did five years earlier, and all of them are now well cited by the standards of the field. To give some points of reference, within the entire new data set a citation count of 40 or more puts a paper in the top 10%, while a citation count of 295 or more puts it in the top 1%. Thus all but one of the twenty papers in table 1 fall in the top 10% and twelve of them fall in the top 1%.
Looking more closely at the table we notice that there are some papers that had very few citations in 2008, some of them only a single citation, particularly the most recent papers at the bottom of the list. The inclusion of these papers in the table is somewhat dubious, since their large z-score rests entirely on the fact of their having received a few citations very shortly after publication (at which time receiving even a single citation is a statistically surprising event). To avoid possible biases, therefore, we henceforth exclude from our reckoning those papers that had received fewer than five citations at the time of our earlier study. Most of the results reported in the remainder of this article are averages for the fifty papers that have the highest z-scores after this culling is performed.

The median number of additional citations received in the last five years, by all 2407 papers from our earlier study, was 10. Among our fifty top-scoring papers the corresponding number is 238. (We quote median figures because the distributions are long-tailed and in such cases means can be strongly dependent on a small number of highly cited papers in the tail. The median does not suffer from this problem.) Thus, the papers we identified have fared very much better than the average. These results suggest that our analysis is capable of identifying papers that will on average receive large numbers of citations in future.

This on its own, however, is not as impressive a feat as it may sound. As discussed in the introduction, the citation process is thought to display preferential attachment, meaning that papers that have received many citations in the past are expected to receive many in the future as well, and there is evidence in support of this hypothesis in our data. Figure 3 shows a scatter plot of the number of new citations received by the papers in our study in the last five years against the number they had at the time of Paper 1 in 2008. As the plot shows, there is a strong positive correlation between the two numbers. If we merely wanted to predict papers that would receive many citations, therefore, it would be easy to do—we just pick papers that have large current numbers of citations. Indeed if we look at the fifty papers from our data set that had the largest numbers of citations back in 2008, we find that the median number of new citations they received in the last five years is 376, even more than the figure of 238 for the fifty papers identified by our z-score analysis.

But this misses the point. The point of our prediction method was to filter out preferential attachment, to identify promising papers even if they had not yet received many citations. For instance, in Paper 1 we singled out the 2006 article by Ohtsuki et al. [16] as a paper that we believed would receive substantial attention in future, even though at that time it had received only 63 citations, a prediction that seems to have been borne out, given that the paper has received an additional 374 citations in the five years since.

One crude way to determine how successful we have been at picking out promising papers of this kind is to calculate not the difference in citation numbers between our first and second measurements, but the ratio. Since the preferential attachment model predicts that the number of new citations received will be proportional to the old number, our null hypothesis under the model is that the ratio of new to old citations should be the same, apart from stochastic fluctuations, for all papers. Thus, we can tentatively identify papers with higher-than-average ratios as having outperformed our expectations.

Looking again at all papers and calculating this new-to-old ratio for each one, we find a median value of 2.00—the median paper had twice as many citations in 2013 as it did in 2008. For the fifty promising papers picked out by our analysis the corresponding figure is more than twice as large, at 5.24. Conversely, the figure for the fifty overall highest-cited papers is just 2.48—only a little greater than the figure for all papers in the data set. In other words, if our goal is to pick papers that will outperform the preferential-attachment null-model expectation, then the strategy of picking papers that already have many citations is a poor one—on average these papers barely beat a random basket of papers. The papers identified by our analysis, on the other hand, do significantly better than average, increasing their citation scores by a factor much greater than that of the typical paper.

This analysis is still not entirely satisfactory, however, since it relies on the assumption of linear preferential attachment. Previous studies suggest that attachment may be nonlinear in practice [17,18] and this appears to be true of our data—the best power-law fit to the data in fig. 3 (shown as the dashed line in the figure) has an exponent somewhat greater than 1. And there is no reason
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Table 2: Twenty of the papers on network science with the highest z-scores in 2013. We predict these papers will receive substantially more citations over the next few years than other papers from the same field with similar current numbers of citations (see footnote 2).

| Year | Author(s) | Reference | 2013 cites | z-score |
|------|-----------|-----------|------------|---------|
| 1998 | Watts D. J. and Strogatz S. H. | Nature 393, 440 | 7807 | 7.043 |
| 1999 | Barabási A.-L. and Albert R. | Science 286, 509 | 7955 | 7.183 |
| 2002 | Milo R. et al. | Science 298, 824 | 1775 | 6.893 |
| 2004 | Newman M. E. J. and Girvan M. | Phys. Rev. E 69, 026113 | 1519 | 9.871 |
| 2005 | Palla G. et al. | Nature 435, 814 | 902 | 9.074 |
| 2005 | Guimerà R. and Amaral L. A. N. | Nature 433, 895 | 683 | 9.142 |
| 2005 | Santos F. C. and Pacheco J. M. | Phys. Rev. Lett. 95, 098104 | 458 | 7.030 |
| 2006 | Newman M. E. J. | Phys. Rev. E 74, 036104 | 431 | 7.963 |
| 2007 | Fortunato S. and Barthélemy M. | Proc. Natl. Acad. Sci. U.S.A. 104, 36 | 418 | 9.148 |
| 2007 | Dosenbach N. U. F. et al. | Proc. Natl. Acad. Sci. U.S.A. 104, 11073 | 371 | 7.312 |
| 2007 | Palla G. et al. | Nature 446, 664 | 281 | 8.441 |
| 2008 | Blondel V. D. et al. | J. Stat. Mech. 2008, P10008 | 287 | 8.924 |
| 2008 | Rosvall M. and Bergstrom C. T. | Proc. Natl. Acad. Sci. U.S.A. 105, 1118 | 258 | 7.806 |
| 2008 | Clauset A. et al. | Nature 453, 98 | 255 | 7.365 |
| 2008 | Santos F. C. et al. | Nature 454, 213 | 226 | 7.769 |
| 2010 | Buldyrev S. V. et al. | Nature 464, 1025 | 192 | 9.002 |
| 2010 | Good B. H. et al. | Phys. Rev. E 81, 046106 | 119 | 8.270 |
| 2010 | Centola D. | Science 329, 1194 | 114 | 7.935 |
| 2011 | Liu Y. Y. et al. | Nature 473, 167 | 126 | 9.289 |
| 2012 | Gao J. X. et al. | Nat. Phys. 8, 40 | 32 | 7.130 |

to assume a power law to be the best functional form. It is possible that the attachment probability could vary in quite a complex manner with the number of citations, the attachment law being substantially different for rarely cited papers from what it is for well-cited ones.

A more robust way to test the citation performance of the papers identified in our analysis is to compare them against a control group, or many control groups, consisting of papers with similar prior citation performance. This allows us to answer the question “Do the papers we have identified perform better than other papers with the same number of citations?”. To this end, we have taken the complete collection of 2407 articles studied in Paper 1 and from them sampled 100 random subsets of papers using Markov chain Monte Carlo. Each of these sets contains fifty papers, like the original set identified in our z-score analysis, and each has the same total number of citations as the original set, which is 10356. Apart from this constraint, however, the sets are drawn at random.

Looking at the papers in these 100 sets, we now find the number of new citations each received in the last five years, the difference between their citation counts in 2013 and 2008. Calculating the median new citations for each set, we find the average figure over all sets to be 15.7 ± 0.4, a much lower number — by a factor of 15 — than the median of 238 measured for the fifty leaders from our analysis. Alternatively, as before, we can compute the ratio of new to old citations, again taking a median for each set, and we find an average figure of 2.23 ± 0.02, not very different from the 2.00 we found for the entire data set (perhaps suggesting that our assumption of linear preferential attachment was a reasonable one). As reported above, the equivalent figure for the set of fifty leading papers was more than twice the size, at 5.24.

By these measures it appears that the predictions of Paper 1 are quite successful. Papers identified using our method outperformed by a wide margin both the field at large and randomly drawn control groups that started out with the same number of citations.

All of these analyses are for papers in the field of network science. It is desirable to test the performance of our prediction method in other fields as well, but unfortunately network science is the only field for which we gave explicit predictions in Paper 1. We do, however, have one other data set from our 2008 study, covering the branch of particle theory concerned with “strange matter”, which is suitable for similar analysis. Although we did not make specific predictions in Paper 1 based on these data, we can revisit the data now and calculate what papers we would have predicted to be highly cited, then test those predictions against current data.

The data on strange matter consist of 1185 papers published between 1984 and 2008, each of which cites one of two foundational papers in the field [19,20]. Duplicating the methodology we used for the network science data set, we have calculated the mean and standard deviation of the number of citations a paper had received in 2008 as a function of publication date, where time is again measured in terms of number of papers published rather than real time (see footnote 1). Then we look for papers whose total citation counts are many standard deviations above the mean. Once again we have picked out the top fifty such papers,
excluding those that had fewer than five citations in 2008.
These papers, we predict, should have received an unusually large number of citations in the five years since the publication of Paper 1.

And indeed we find this to be the case. The median number of new citations received by these top fifty papers in the last five years is 39, while the median number received by papers in the data set as a whole is just 2. Both numbers are significantly smaller than the corresponding numbers for the network science data set, presumably because strange matter is a smaller and less active field, but the ratio of 19 between them is remarkably close to the ratio of 23 for network science —papers picked out by our method do about a factor of 20 better than the average paper in both cases. As with the network science data set, however, it is perhaps more interesting to compare not to the data set as a whole, but to random control groups. Again, therefore, we have generated 100 control groups of fifty papers each, drawn at random from the data set but constrained to have the same total number of citations as the original group of fifty (which is 8190). We calculate the median number of new citations for each of these groups, and find an average figure of 5.3 ± 0.1, still more than a factor of 7 lower than the figure for the top fifty predictions. Again, it appears that our predictions are borne out.

**New predictions.** — Encouraged by these results and capitalizing on the fact that we have a new data set of papers in network science and their citations up to the year 2013, we have also applied our methods to the new data to make predictions about papers that will be highly cited in the next few years. Working with the entirety of our new 6976-paper network data set, we again calculate the mean and standard deviation of the numbers of citations received as a function of time and look for the papers with the highest z-scores. Table 2 is the equivalent of table 1 for this new analysis, listing twenty of the papers with the highest z-scores within the field of network science. It will be interesting to see whether these predictions in turn come true.

**Conclusions.** — In this paper we have revisited predictions made in 2008 of scientific papers that, according to those predictions, should receive above average numbers of citations, even though they may not yet have had many citations at that time. Looking at those predictions five years on, we find that the papers in question have indeed received many more citations than average papers in the same fields. Indeed they have received substantially more even than comparable control groups of randomly selected papers that were equally well cited in 2008. Because of the so-called preferential attachment effect, one can quite easily identify papers that will do well just by looking for ones that have done well in the past. But the papers identified by our analysis did well even when one controls for this effect, indicating that the analysis is capable of identifying papers that will be successful not merely because they already have many citations. We hope, though we cannot prove, that the additional factors driving this success are factors connected with paper quality, such as originality and importance of research and quality of presentation.

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