The Growth of Physics and Mathematics

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ABSTRACT
This paper studies scientific commercial journals in the fields of physics and mathematics. We study the changes in the number of authors, number of pages, and number of citations per paper. We also study the fluctuations in the number of papers each scientist will publish in a lifetime. The factors we consider include: the number of large collaborations, the pressure on each scientist to publish, and funding availability.

INTRODUCTION
In 1975 D. de Solla Price published Diseases of Science in which he studied the "size of science." He defined this as "the magnitude of the effort in terms of numbers of men working, papers written, discoveries made, financial outlay involved." As a continuation of his paper, our research studies Price's predictions and the growth of science since 1970 in the specific fields of Physics and Mathematics. In this paper we define a scientist as an active researcher who has published at least one paper in an American journal. We assume that the number of American scientists publishing exclusively in foreign journals is offset by the number of foreign scientists published in American journals. Therefore this research should accurately reflect the size of science in the United States.


Society Published Journals
Society published journals are supported through subscriptions, page and reprint charges and financial support from professional organizations. The evolutions of these journals vary. In mathematics a new specialization usually results in the creation of a new journal. In Physics, the addition of a new specialization is often treated by the addition of a new subsection or the sub-discipline separation of an already existing journal, in which case the pre-existing journal continues to grow.

The Astrophysical Journal
The number of papers per year in the ApJ (Figure 1) beautifully illustrates the trend discussed in the Diseases of Science. In 1970, an approaching crisis loomed. With 13,728 pages and 1200 authors, the journal was becoming unmanageable. In 1974, in an attempt to control its size, issues of this journal increased both in height and width. The bi-monthly journal was forced to increase its size again in 1983, but the number of pages still topped 10,000. In 1990 the journal expanded publication to three times a month. The graph clearly shows exponential growth and one can easily project that the number of pages in the journal this year will exceed 25,000.1

A notable trend in ApJ is the number of authors per paper. The ApJ has experienced a steady growth in the average number of authors per paper from 2.36 in 1970 to 6.72 in 1995. This growth in collaborative efforts is most likely due to the tremendous amount of technological support required to conduct research. This is a common trend in Physics journals and also occurs in the JAS and Phys. Rev. C.

The Journal of Atmospheric Science
The number of the pages in the JAS fluctuated during the 20 years studied with no noticeable trend. The least number of pages and papers occurred in 1977, when there were 2022 pages and 185 papers published (Figure 2). In 1984 the publication frequency of the journal increased from twelve to twenty-four issues a year. There was a peak in pages and papers, 4560 and 302, respectively, in 1995. In 1997, there were 2901 pages and 169 papers published. The current size of this journal does not indicate any large-scale downward trend.

1 In fact, the 1998 ApJ contained 28,000 pages!
FIGURE 1. Papers per year published in the ApJ. Some important years to note are 1980, when the IUE (International Ultraviolet Explorer) papers began to be contributed to the journal; 1990, which brought an increase of papers due to the HST (Hubble Space Telescope) and COBE (Cosmic Background Explorer) projects; and 1995, when HST II (the second phase of the Hubble Space Telescope project) began.

The JAS experienced considerable growth in the number of papers published in 1995. A few papers dealt with large-scale flooding in the summer of 1993. A cluster of papers analyzed the Atlanta Stratocumulus Transition Experiment (ASTEX). Most of this growth may, however, be attributed to the El Niño Southern Oscillation (ENSO) in 1991-1992. Little is known about the causes of this phenomenon, many weather anomalies are associated with it, for example: tropical heating and squall lines in the tropics. There has been a significant increase in interest concerning these climatic oscillations. Large amounts of media attention was given to the most recent "El Niño." Because the event, or rather its name, has gained popularity, any information that leads to a greater understanding of the phenomenon also receives a great deal of attention.

Physical Review

The venerable Physical Review split into four separate parts in 1970. Phys. Rev. C is the Nuclear Physics division of the journal. The Rapid Communications section of the Phys. Rev. C is not counted in our study in order to avoid double counting, since more complete results are generally published as articles in later issues. In 1970 the average length and authors per paper were 8.4 and 2.63, respectively. Phys. Rev. C distinguished six sub-categories in 1976. In 1979, the average number of authors per paper was 3.47 with 9.48 pages per paper and 39 papers per issue. In 1983, the journal increased the size of its pages from 7.5" x 10.5" to 8" x 11" which temporarily reduced the number of pages per year. One year later, in 1984, there were 4.22 authors per paper and 8.7 pages per paper. In 1991, the journal defined even more specialized sub-categories. By 1994, the journal averaged 50 articles per issue, 5.84 authors per paper and 9.39 pages per paper. The total number of pages in the journal per year has increased by 19.22% every five years, or 3.84% increase per year, starting in 1984! Price argued that the bigger the journal, the faster it grows. If this is true for the Phys. Rev. C journal may reach 10,000 pages a year within a decade or so. What does this change mean to the different subsections of the journal? Is this growth a contribution of all the subsections or just a few and how are these subsections related to each other?

FIGURE 2. Papers per year for the JAS


In Phys. Rev. C, nuclear structure papers represent anywhere from 4-28% of the total papers in the volume. This percentage was found by studying the first issue of the journal in 1979, and the 1986 and 1997 issues (Table 1). In 1979, there were eight papers in this field, and the majority of them were theoretical. In 1986 all five published papers were theoretical. By 1997, there were more experimental than theoretical papers, which made up 13% of the total papers pub-
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lished in that issue. One reason for the increase in the experimental papers is continuing improvements in the experimental equipment, techniques, computing and data recording systems. Phys. Rev. C also publishes a large number of papers on nuclear reactions (13-32% of the total papers). The publishing of a large number of reaction papers is followed in a few years by a large number of nuclear structure papers. The correlation between these two types of papers could also be due to technological improvements. For example, the recent ability to produce radioactive beams will allow experimenters to study different reactions and produce new isotopes in the laboratory. This will likely lead to an increase in nuclear reaction papers and possibly more nuclear structure papers.

<table>
<thead>
<tr>
<th>Year</th>
<th>1979</th>
<th>1986</th>
<th>1997</th>
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<tbody>
<tr>
<td>E</td>
<td>T</td>
<td>E</td>
<td>T</td>
</tr>
<tr>
<td>Total Papers</td>
<td>2</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>Authors</td>
<td>3</td>
<td>2.5</td>
<td>0</td>
</tr>
<tr>
<td>Pages</td>
<td>11</td>
<td>7.5</td>
<td>0</td>
</tr>
<tr>
<td>Cites</td>
<td>31</td>
<td>24.2</td>
<td>0</td>
</tr>
<tr>
<td>Total Papers (January Issue)</td>
<td>30</td>
<td>37</td>
<td>55</td>
</tr>
</tbody>
</table>


The Bulletin of the American Mathematical Society

The Bulletin is a clear counterexample to the other journals we studied. This journal contradicts Price’s prediction that scientific literature grows exponentially. The total number of papers printed in the Bulletin decreased sharply from 190 published in 1970 to only 11 published in 1997 (Figure 4). From this graph, one might think that this journal is dying. However, the total number of math journals available is increasing rapidly, which forces long standing journals to change their editorial policy. The decrease in the number of scientific papers published in the Bulletin has been compensated by an increase in the length of each paper. The average length of an article increased from 6.3 pages in 1970 to 26.6 pages in 1997. Style changes during this period have been minor and acted to both increase and decrease the typical article size, so the increase in pages is strictly caused by a change in content. The other journals we are covering have not had such a drastic change in the size of each paper because, unlike the Bulletin and most other mathematics journals, they have page charges. In addition to the increase of paper length, the Bulletin also has seen a steady increase in the number of book reviews published, from 15 in 1970 to 61 reviews in 1996.

As most mathematicians will verify, any major new subject is typically greeted by the creation of several new journals. Figure 5 shows an approximate count of the number of math journals that were in print for the sample years.2 This situation forces most mathematics journals to find a specific niche, and does not allow much room for a journal to shift its focus without stepping on the toes of another journal.

COMMERCIAL JOURNALS

Commercial journals are funded only by advertisements and subscriptions. Journals of this type are refereed commercial enterprises owned by publishing companies. They are in magazine format with color, glossy pages. Typically there are no page charges but it is very expensive for authors to obtain reprints.

The data for this graph was collected from each journal subscribed to by the University of Notre Dame Mathematics Library.
Optics Communications

Optics Communications is owned by Elsevier, the largest scientific publisher in the world. Acknowledgments for funding of individual studies are conspicuously absent from the papers. The birth of the journal in 1970 saw the monthly publication of about 180 papers approximately 3.75 pages long for a total of 650 pages. In 1980, the number of pages had more than doubled to 1530, with 438 papers per year. The length of each paper had also grown to five pages. In 1981 the journal became a bi-monthly publication, and a small section of longer papers (averaging 13 pages) was added. While the publication frequency of Optics Communications has remained the same, the number of pages has exploded to 14,048 and number of papers to 688 in 1997.

The growth of Optics Communications has not been as striking as that of the ApJ. This may be due to commercial controls on its size. The sharp rise in the number of page per year does not appear to be continuing. Figures for 1998 are showing approximately 250 pages per issue and about 37 papers per issue. There has also been a decrease in the number of full length papers submitted to about 10 per issue.

![Figure 6](image1)

**Figure 6.** The total number of papers published in Optics Communications.

**Scientists in the Field**

Since there has clearly been an increase in the amount of scientific publishing, it is natural to wonder whether the increase is due solely to an increase in the number of scientists in the field. To answer this question we also studied the correlation between the number of scientists and the number of publications in the respective fields. There are a few ways to find this. One way to track the number of scientists is to look at society membership statistics. Since it’s founding in 1899 the American Physics Society (APS) experienced a steady growth in membership until 1994 (Figure 7). Membership dropped off between 1994 and 1997, and then increased again. The growth of membership in mathematical societies (specifically Society of Industrial and Applied Mathematics (SIAM)) show a similar trend (Figure 8).

![Figure 7](image2)

**Figure 7.** The total number of American Physics Society members since its founding in 1899. After a brief dip between 1994 and 1996, the membership continues to increase.

![Figure 8](image3)

**Figure 8.** The number of SIAM members per year.

This increase in the number of scientists can also be seen in the number of degrees awarded. Figure 9 shows the number of Bachelors and PhDs awarded in Physics and Astronomy from 1960 to 1997. As can be seen in this graph, the number of bachelor’s degrees awarded peaks in 1965, followed by a peak in the number of PhDs awarded in the early 1970s. It is therefore distressing that the large peak in undergraduate degrees in 1970 is not followed by a large peak in PhDs around 1975. If this trend continues, the decrease in the number of undergraduate degrees awarded in recent years will lead to a decrease in the number of PhDs awarded in these fields. A higher number of undergraduates may not be continuing on to graduate school. Yet, looking at the PhD trend, the number of degrees awarded is increasing, implying an increase in the number of scientists in the field.
According to a paper by Abt (1982), astronomers publish their largest number of papers the year following the awarding of a PhD and again about 5 to 8 years later. If this is true, the 60 people awarded their PhDs in Astronomy in 1975 should have contributed to the literature in 1976, and 1980 to 1983. This could be a contributing factor to the increases described in the first section. There were 192 degrees awarded in Astronomy and Astrophysics in 1996. If Abt is correct, there should be an increase in the number of papers each of these scientists published in 1997 and between 2002 and 2004, adding to an increase in the literature.

As the "size of science" increases, there has been an increase not only in the number of scientists in the field but also in the number of papers published by each author and in the incidence of larger collaborations. The previous section demonstrated the increase in the average number of authors per paper. In 1975, Price found that each scientist produces a career total of about three papers. This is not true today; most scientists will exceed this number of publications. For instance, H.G. Börner, a nuclear physicist who developed the GRID (Gamma-Ray-Induced-Doppler broadening) technique for measuring lifetimes in nuclei has (co)authored 148 papers in his 24 year career or 6.16 papers per year. Another example is the mathematician Paul Erdős, who (co)authored over 1200 papers in his lifetime, or an average of about 20 papers per year! More generally, in the JAS, it is clear that the number of papers per author has increased steadily in the last twenty years (Table 2). In 1993, the National Science Foundation conducted a study of around 10 million scientists and engineers. From these data, we find a lower limit of 4.6 published papers per author in his or her lifetime. Since the scientists surveyed are still working in the field and have not finished publishing, this number will be higher for lifetime publications. Obviously, not every author writes 20 papers per year, but it is clear that the average number of papers per scientist per year is increasing.

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of papers</th>
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<tbody>
<tr>
<td>1977</td>
<td>2</td>
</tr>
<tr>
<td>1986</td>
<td>8</td>
</tr>
<tr>
<td>1996</td>
<td>12</td>
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Table 2. Authors with 3 or more papers in JAS for 1998.

There are likely several reasons for this increase in publications per author. One is the importance of publishing to academics. The number of publications is a determining factor for advancement at a university. It can also affect a scientist's ability to compete for grants; the emphasis on publishing is linked to the competition for National Science Foundation (NSF) money. This government funding has taken the research out of commercial laboratories and into universities and national laboratories. In atmospheric science, an increase in the number of weather satellites has yielded an increase in available data, which has likely led to the increase in the number of papers in the field and per author. It is important to note that even with the increase in the number of papers published by each scientist, no single group is responsible for the majority of the publications in the field.

If this trend continues, the literature will continue to increase even if the number of new scientists decreases. With all of these papers to read, how do scientists determine which ones represent significant scientific discoveries?

**CITATION PATTERNS**

Citation patterns vary depending on the field. Abt (1998) examined these patterns in different journals; Table 3 shows a portion of what he called the half-lives of papers in different disciplines. For example, suppose a paper receives $n$ citations in its lifetime and has a half-life of 10 years. Then, in the first 10 years it receives $n/2$ citations, and in the next 10 years it will receive $n/4$ citations, and so on. Abt's conjecture was that the half-life of a paper depends on the length of the paper and also significantly depends on the rate of growth of the field. Our data supports this conjecture and we can expect the ApJ to have grown more than Phys. Rev.

If the Size of Science is growing exponentially, how do we measure the quality of these papers? Let us...
<table>
<thead>
<tr>
<th>Journal</th>
<th>Papers</th>
<th>Half-life (years)</th>
<th>Half-life (Corrected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ApJ</td>
<td>165</td>
<td>29.3</td>
<td>8.0</td>
</tr>
<tr>
<td>Phys. Rev.</td>
<td>123</td>
<td>10.6</td>
<td>5.9</td>
</tr>
</tbody>
</table>

Table 3. Half-lives of scientific papers calculated in years and also corrected for growth.

Consider the Science Citation Index (SCI). The SCI lists the number of times a paper has been cited by listing the papers in which it was cited. For example, H.G. Börner published two extremely significant papers around 1990 pertaining to the GRID technique (Börner et al. 1988; Börner et al. 1991). These papers have been cited 26 and 49 times respectively. This fact may lead us to consider the Science Citation Index as a measure of a paper’s usefulness and importance in the field. Unfortunately, a significant paper may go uncited, and its importance will not be recognized. Furthermore, the number of citations a paper receives does not necessarily imply its contribution is significant to the field. For example, the well respected geologist Vishwa Jit Gupta published dozens of papers and was cited hundreds of times for his work in the Himalayan region. This work was later found to be fraudulent by John Talent (1989). Thus, we conclude that the Science Citation Index, though important, may not be the best choice for a quality standard.

**REFERENCES**


**CONCLUSION**

“Science” is a very general term that encompasses many disciplines. The general size of science is increasing; however, the size of each field may not be. One way to analyze the size of a field is to analyze research published in the field. There are hundreds of journals in which scientists can publish. Motivation for publishing varies among the disciplines and even among the scientists within the fields.

**REFERENCES**


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