

Citation Statistics From 110 Years of Physical Review

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Publicly available data reveal long-term systematic features about citation statistics and how papers are referenced. The data also tell fascinating citation histories of individual articles.

Introduction

The first particle published in the *Physical Review* was received in 1893; the journal's first volume included 6 issues and 24 articles. In the 20th century, the *Physical Review* branched into topical sections and spawned new journals. Today, all articles in the *Physical Review* family of journals (PR) are available online and, as a useful byproduct, all citations in PR articles are electronically available.

The citation data provide a treasure trove of quantitative information. As individuals who write scientific papers, most of us are keenly interested in how often our own work is cited. As dispassionate observers, we can use the citation data to identify influential research, new trends in research, unanticipated connections across fields, and in subfields that are exhausted. A certain pleasure can also be gleaned from the data when they reveal the idiosyncratic features in the citation histories of individual publications.

The investigation of citation statistics has a long history¹ in which a particularly noteworthy contribution was a 1965 study by Derek John de Solla Price². In his study, Price built upon original models by George Yule and Herbert Simon³ to argue that the distribution in the number of citations to individual publications had a power-law form. Price also noted that well-cited papers continue to be referenced more frequently than less-cited papers, and coined the term cumulative advantage to describe the mechanism that causes a persistently higher rate⁴. Cumulative advantage means that the probability that a publication is cited is an increasing function of its current number of citations.

In the framework of current fashionable evolving network models, the mechanism is called preferential attachment⁵. Linear preferential attachment models provide appealing explanations for the power-law distributions of connections that are observed in many social systems, natural networks, and manmade networks such as the World Wide Web⁶. One fundamental motivation for studying citation statistics is to determine whether they

exhibit some of the universal features that have been ascribed to prototypical models of evolving networks^{5,7,8}.

Before examining the citation data, I offer several caveats: First, the data include only internal citations — that is, citations from PR articles to other PR articles — and are perforce incomplete. For highly cited papers, a previous study⁹ found that total citations typically outnumber internal ones by a factor of 3 to 5, a result that gives a sense of the incompleteness of the PR data. Second, some 5–10% of citations appear to be erroneous^{9,10}, although the recent practice by PR of crosschecking references when manuscripts are submitted has significantly reduced the error rate. Third, papers can be highly cited for many reasons — some substantive and some dubious. Thus the number of citations is merely an approximate proxy for scientific quality.

Citation distribution and attachment rate

The PR citation cover 353,268 papers and 3,110,839 citations from July 1893 through June 2003. The 329,847 publications with at least 1 citation may be broken down as follows:

| | |
|---------------------------|------------------|
| 11 publications with | > 1000 citations |
| 79 publications with | > 500 citations |
| 237 publications with | > 300 citations |
| 2,340 publications with | > 100 citations |
| 8,073 publications with | > 50 citations |
| 245,459 publications with | < 10 citations |
| 178,019 publications with | < 5 citations |
| 84,144 publications with | 1 citation |

A somewhat depressing observation is that nearly 70% of all PR articles have been cited less than 10 times. (The average number of citations is 8.8.) Also evident is the small number of highly cited publications; table I lists the 11 publications with more than 1000 citations.

Citations have grown rapidly with time, a feature that mirrors the growth of PR family of journals. From 1893 until World War II, the number of annual citations, from PR publications doubled approximately every 5.5 years. The number of PR articles published in a given year also doubled every 5.5 years. Following the publication crash of the war years, the number of articles published annually doubled approximately every 15 years.

The citation data naturally raise the question, What is the distribution of citations? That is, what is the probability $P(k)$ that a paper gets cited k times? This question was investigated by Price, who posited the power law

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$P(k) \propto k^{-\nu}$, with ν positive. A power-law form is exciting for statistical physicists because it implies the absence of a characteristic scale for citations — the influence of a publication may range from useless to earth-shattering. The absence of such a characteristic scale in turn implies that citations statistics should exhibit many of the intriguing features associated with phase transitions, which display critical phenomena on all length scales.

Somewhat surprisingly, the probability distribution derived from more than 3 million PR citations still has significant statistical fluctuations. It proves useful to study the cumulative distribution, $C(k) = \int_k^\infty P(k') dk'$, the probability that a paper is cited at least k times, to reduce these fluctuations.

On a double logarithmic scale, $C(k)$ has a modest negative curvature everywhere. That behavior, illustrated in Fig. 1, suggests that the distribution decays faster than a power law and is at variance with previous, smaller-scale studies that suggested either a power-law^{2,11} or a stretched exponential form¹², $P(k) \propto \exp(-k^\beta)$, with $\beta < 1$. It is intriguing that a good fit over much of the range of the range of the distribution is the log-normal form $C(k) = A e^{-b \ln k - c(\ln k)^2}$. Log-normal forms typically underlie random multiplicative processes. The describe, for example, the distribution of fragment sizes that remain after a rock has been hammered many times.

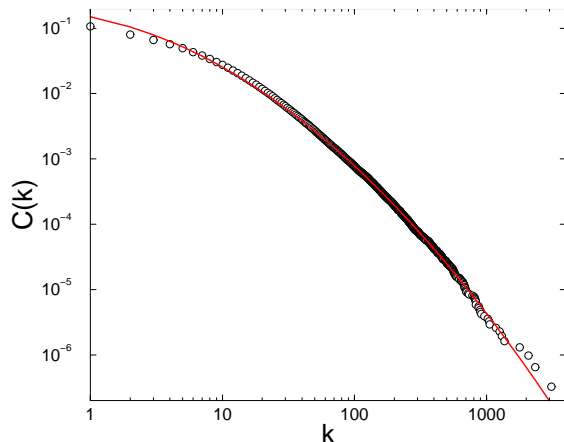


FIG. 1: **The cumulative citation distribution** $C(k)$ versus the number of citations k for all papers published from July 1893 through June 2003 in the *Physical Review* journals. Circles indicate the data. The curve is the log-normal fit $C(k) = A e^{-b \ln k - c(\ln k)^2}$, with $A = 0.15$, $b = 0.40$, and $c = 0.16$.

The development of citations may be characterized by the attachment rate A_k , which gives the likelihood that a paper with k citations will be cited by a new article. To measure the attachment rate, first count the number of times each paper is cited during a specified time range; this gives k . Then, to get A_k , count the number of times each paper with a given k in this time window was cited in a subsequent window. As shown in Fig. 2, the data suggest that A_k is a linear function of k , especially for $k <$

150, a condition that applies to nearly all PR papers¹³. Thus linear preferential attachment appears to account for the propagation of citations.

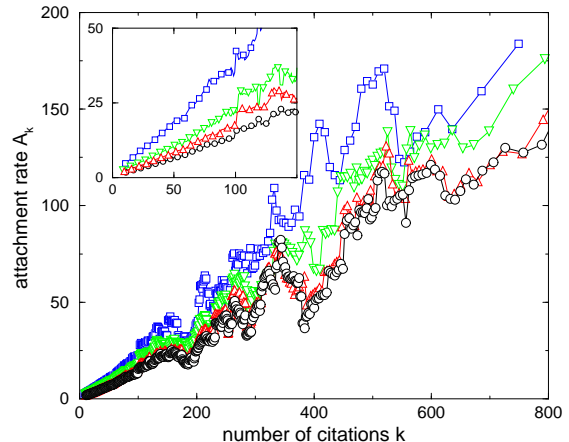


FIG. 2: **The attachment rate** A_k is a nearly linear function of the number of citations k , especially for k less than 150 (inset). The different colors indicate different year ranges for establishing k : 1990-1999 (blue squares), 1980-1999 (green ∇), 1970-1999 (red \triangle), and 1893-1999 (black \circ). The rate A_k is determined from citations in the year 2000. Data have been averaged over a range of $\pm 2.5\%$. Other time ranges for existing and new citations give similar behavior.

Linear attachment, though, leads to two paradoxes. First, a linear rate implies a power-law citation distribution, but Fig. 1 indicates that the data are better described by a log-normal form. While a log-normal distribution does arise from the nearly linear attachment rate $A_k = k/(1 + a \ln k)$, with a positive, Fig. 2 hints that A_k may be growing slightly *faster* than linearly with k . Second, to implement linear preferential attachment consciously, a citer must be aware of the references to every existing paper. That's clearly not realistic. A more realistic process that can lead to linear preferential attachment is the redirection mechanism^{7,14}. In redirection, an author who is writing the reference list for a paper figuratively picks a random paper. Then the author cites either the random selected paper (with probability $1 - r$) or one of the references within that paper (with probability r). This purely local mechanism generates the linear form $A_k = k + (\frac{1}{r} - 2)^7$. Still a mystery is why the myriad of attributes that influences whether a paper gets cited manifests itself as a citation rate that is a nearly linear function of the number of citations.

Age structure

A common adage says that nobody cites classic papers anymore. Is this really true? How long does a paper continue to get cited?

The age of a citation is the difference between the year when a citation occurs and the publication year of the

cited paper. Typically, unpopular papers are cited soon after publication, if at all, and then disappear. The converse is also true. For example, the average citation age $\langle a \rangle$ over the entire PR data set is 6.2 years, but articles published before 2000 for which $\langle a \rangle$ is less than 2 years receive, on average, only 3.6 citations. On the other hand, highly cited papers usually continue to be cited for a long time, and vice versa. Papers with more than 100 citations have $\langle a \rangle = 11.7$ years, and the 11 publications with more than 1000 citations have $\langle a \rangle = 18.9$ years. For all PR publications with 500 or fewer citations, the average citation age grows with the number of citations roughly as $\langle a \rangle = k^\alpha$, with $\alpha \approx 0.3$.

The citation age distributions — that is, the number of citations as a function of age — reveal a fact that is surprising at first sight: The exponential growth of PR articles strongly skews the form of the age distributions! There are, in fact two distinct age distributions. One is the distribution of *citing* ages, defined as the number of citations of a given age *from* a paper. Remarkably, citing memory is independent of when a paper is published. An author publishing now seems to have the same range of memory as an author who published an article 50 years ago. The citing age distribution roughly decays exponentially in age, except for a sharp decrease in citations during the period of World War II. However, citing an old paper is difficult a priori simply because relatively few old publications exist. As noted by Hideshiro Nakamoto¹⁵, a more meaningful citing age distribution is obtained by rescaling the distribution by the total number of publications in each citing year. So, if one is interested in journal citations from 2005, the number of cited papers that are, say, four years old should be scaled by the total number of papers published in 2001. The rescaling has a dramatic effect: The nearly exponential citing age distribution is transformed into a power-law! An analogous skewing due to the rapid growth of PR articles also occurs in the distribution of *cited* ages, that is, the number of citations of a given age *to* an article.

Individual citation histories

The citation histories of well-cited publications are diverse from the collective citation history of all PR articles. The varied histories roughly fall into classes that include revived classic works or “sleeping beauties”¹⁶, major discoveries, and hot publications. It’s fun to examine examples of each class.

Sometimes a publication will become in vogue after a long dormancy — a revival of an old classic. I arbitrarily define a revived classic as a nonreview PR article, published before 1961, that has received more than 250 citations and has a ratio of the average citation age to the age of the paper greater than 0.7. Thus, revived classics are well-cited old papers with the bulk of their citations occurring long after publication. Only the 12 papers listed in table II fit these criteria.

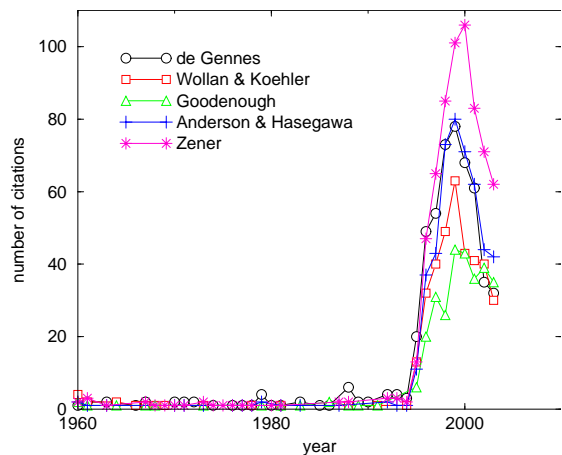


FIG. 3: **Five revived classics** of relevance to colossal magnetoresistance have similar citation histories. Table II gives more information about these papers.

The clustered citation histories of the five articles plotted in in Fig. 3 are particularly striking. These articles, published between 1951 and 1960 (with three in the same issue of *Physical Review*), investigated the double exchange mechanism in Perovskite manganites, the mechanism responsible for the phenomenon of colossal magnetoresistance. This topic became in vogue in the 1990’s because of the confluence of new synthesis and measurement techniques in thin-film transition-metal oxides, the sheer magnitude of the effect, and the clever use of the term “colossal”. The citation burst more than 40 years after the publication of these five articles is unique in the history of the PR journals.

The other seven papers have different claims to fame. Eugene Wigner’s 1932 paper had 115 citations before 1980 and 447 through June 2003. Similarly, the Albert Einstein, Boris Podolsky and Nathan Rosen (EPR) paper had 36 citations before 1980 and 456 more through June 2003. With average citation ages of 55.8 and 59.6 respectively, these are the longest-lived articles with more than 35 citations in the PR family. Those papers, as well as the one by Yakir Aharonov and David Bohm, owe their renewed popularity to the upsurge of interest in quantum information phenomena. Wigner’s 1934 papers deals with correlations in an electron gas, a problem of enduring interest in condensed matter physics. Julian Schwinger’s work is a classic contribution to quantum electrodynamics. The 1958 publication by Philip Anderson helped launched the field of localization. And Richard Feynman’s paper presented a widely applicable method for calculating molecular forces. Feynman’s article is noteworthy because it is cited by all PR journals (except the accelerators and beams special topics journal).

Publications that announce discoveries often receive a citation spike when the contribution becomes recognized. I arbitrarily define a discovery paper as having more than 500 citations and a ratio of average citation age to

publication age less than 0.4; I exclude articles published in *Reviews of Modern Physics* and compilations by the Particle Data Group. Table III lists the 11 such discovery papers; all were published between 1962 and 1991. A trend in this group of papers is the shift from elementary-particle physics (the six articles published before 1976) to condensed-matter physics (the five articles published after 1983). The earlier discovery papers reflected major developments in elementary-particle physics, including $SU(3)$ symmetry, the prediction of charm, and grand unified theories. The condensed matter articles are on quasicrystals, multifractals, and high-temperature superconductivity. If the citation threshold is relaxed to 300, an additional seven papers fit the discovery criteria. All of these are concerned with high-temperature superconductivity, and all but one appear during the golden age of the field, 1987–89.

It is not clear whether the shift in the field of discovery publications stems from a sea change in research direction or because of from prosaic concerns. The past 15 years have seen a major upsurge in quantum condensed-matter physics that perhaps stems from the discovery of high-temperature superconductivity. But recent elementary-particle physics discoveries may be underrepresented in PR because many CERN-based discoveries have been published in journals outside the PR family.

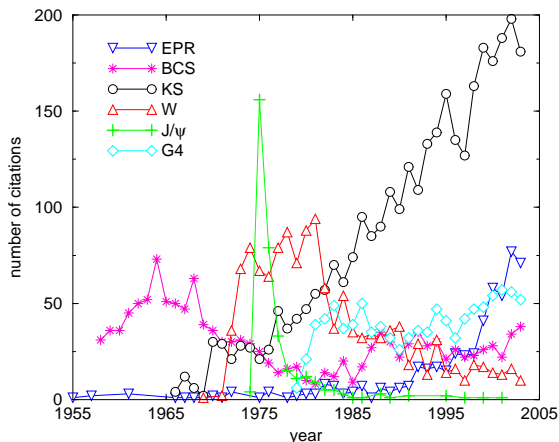


FIG. 4: **Six classic**, highly-cited publications have varied citation histories. The abbreviations are defined in the text.

A number of classic, highly cited publications have noteworthy citations histories. Fig. 4 illustrates some of these histories. Citations to “Theory of Superconductivity”, Phys. Rev. **108**, 1175 (1957) by John Bardeen, Leon Cooper and J. Robert Schrieffer (BCS) closely track the activity in superconductivity; the paper received its fewest citations in 1985, the year before the discovery of high-temperature superconductivity. The BCS paper is the earliest with more than 1000 citations in the PR family. Steven Weinberg’s paper (W) “A Model of Leptons”, on the electroweak theory, (Phys. Rev. Lett. **19**, 1264 (1967)), has a broad citation peak followed by a relatively slow decay as befits this seminal paper’s long-

term influence. On the other hand, the average citation age for the 1974 publications that announced the discovery of the J/ψ particle – Phys. Rev. Lett. **33**, 1404 and 1406 (1974) – is less than 3 years!

An unusual example is “Scaling Theory of Localization: Absence of Quantum Diffusion in Two Dimensions”, Phys. Rev. Lett. **42**, 673 (1979) by Elihu Abrahams, Anderson, Don Licciardello and T. V. Ramakrishnan (the so-called gang of four; G4). Since publication, the G4 paper has been cited 30–60 times annually, a striking testament to its long-term impact. The paper with the most citations in all PR journals is “Self-Consistent Equations Including Exchange and Correlation Effects”, Phys. Rev. **140**, A1133 (1965) by Walter Kohn and Lu Sham (KS). Amazingly, citations to this publication have been steadily increasing for nearly 40 years.

The KS paper is also an example of what may be called a hot paper, defined as a nonreview paper with 350 or more citations, a ratio of average citation age to publication age greater than two-thirds, and a citation rate increasing with time. Ten papers, listed in table IV, fit these criteria. The 1932 Wigner and 1935 EPR articles, both more than 70 years old, and the two most-cited PR papers of all time, KS and the 1964 article by Pierre Hohenberg Kohn, are all still hot. Astounding!

Of the remaining six hot papers, five are in quantum condensed-matter physics. Three of them build on the formalism introduced in the seminal articles by Hohenberg and Kohn and by Kohn and Sham. Another, Anderson’s 1958 localization paper, can be viewed both as hot and as the revival of a classic. The newest hot article, by Charles Bennett and coauthors, is concerned with quantum information theory, a research area that has recently become fashionable and also led to the sharp increase in citations to Wigner’s 1932 paper and the 1935 EPR paper.

A unique window

A small number of physicists have played a remarkably large role in top-cited PR publications. Two individuals have coauthored five papers from among the top 100 cited PR articles⁹: Kohn, who occupies positions 1, 2, 24, 96, and 100, and Anderson, with positions 9, 19, 20, 35, and 41. Wigner appears four times (4, 8, 53, and 55), and Lars Onsager (16, 64, and 68) and John Slater (12, 27, and 40) each appear three times.

The PR citation data provide a unique window with which to study the development of citations, and the work I have described can be extended and applied in many ways. For example, constructing a graphical representation of the entire dynamically changing citation network should be revealing. Such a graph could show how fields develop and could expose unexpected connections between disparate areas. A practical, if more controversial, use of citation data would be to construct retrospective journals that include only highly cited papers.

Such journals would provide a welcome reduction in the total literature volume, because only 30% of all articles have more than 10 citations and a mere 2.3% have more than 50 citations. A repository for all publications would still be necessary, as sleeping beauties do emerge long after publication.

Acknowledgments

I thank Mark Doyle of the American Physical Society

editorial office for providing the citation data, Jon Kleinberg for initial collaboration, Andy Cohen and Andy Millis for literature advice, an anonymous referee for pointing out Nakamoto's work, Paul Krapivsky and Mark Newman for helpful manuscript suggestions, and Claudia Bondila and Guoan Hu for writing Perl scripts for some data processing. Finally, I am grateful to NSF grant DMR0227670 (BU) and DOE grant W-7405-ENG-36 (LANL) for financial support.

TABLE I: *Physical Review* articles with more than 1000 citations through June 2003. *PR*, *Physical Review*; *PRB*, *Physical Review B*; *PRD*, *Physical Review D*; *PRL*, *Physical Review Letters*; *RMP*, *Reviews of Modern Physics*.

| Publication | # cites | Av. Age | Title | Author(s) |
|------------------------------|---------|---------|--|--|
| PR 140 , A1133 (1965) | 3227 | 26.7 | Self-Consistent Equations Including Exchange and Correlation Effects | W. Kohn, L. J. Sham |
| PR 136 , B864 (1964) | 2460 | 28.7 | Inhomogeneous Electron Gas | P. Hohenberg, W. Kohn |
| PRB 23 , 5048 (1981) | 2079 | 14.4 | Self-Interaction Correction to Density-Functional Approximations for Many-Electron Systems | J. P. Perdew, A. Zunger |
| PRL 45 , 566 (1980) | 1781 | 15.4 | Ground State of the Electron Gas by a Stochastic Method | D. M. Ceperley, B. J. Alder |
| PR 108 , 1175 (1957) | 1364 | 20.2 | Theory of Superconductivity | J. Bardeen, L. N. Cooper, J. R. Schrieffer |
| PRL 19 , 1264 (1967) | 1306 | 15.5 | A Model of Leptons | S. Weinberg |
| PRB 12 , 3060 (1975) | 1259 | 18.4 | Linear Methods in Band Theory | O. K. Andersen |
| PR 124 , 1866 (1961) | 1178 | 28.0 | Effects of Configuration Interaction on Intensities and Phase Shifts | U. Fano |
| RMP 57 , 287 (1985) | 1055 | 9.2 | Disordered Electronic Systems | P. A. Lee, T. V. Ramakrishnan |
| RMP 54 , 437 (1982) | 1045 | 10.8 | Electronic Properties of Two-Dimensional Systems | T. Ando, A. B. Fowler, F. Stern |
| PRB 13 , 5188 (1976) | 1023 | 20.8 | Special Points for Brillouin-Zone Integrations | H. J. Monkhorst, J. D. Pack |

TABLE II: The 12 revived classics, as defined in the text, arranged chronologically. *PR*, *Physical Review*.

| Publication | # cites | Av. Age | Title | Author(s) |
|-----------------------------|---------|---------|--|------------------------------------|
| PR 40 , 749 (1932) | 561 | 55.8 | On the Quantum Correction for Thermodynamic Equilibrium | E. Wigner |
| PR 46 , 1002 (1934) | 557 | 51.5 | On the Interaction of Electrons in Metals | E. Wigner |
| PR 47 , 777 (1935) | 492 | 59.6 | Can Quantum-Mechanical Description of Physical Reality Be Considered Complete? | A. Einstein, B. Podolsky, N. Rosen |
| PR 56 , 340 (1939) | 342 | 49.3 | Forces in Molecules | R. P. Feynman |
| PR 82 , 403 (1951) | 643 | 46.4 | Interaction between <i>d</i> -Shells in Transition Metals. II. Ferromagnetic Compounds of Manganese with Perovskite Structure | C. Zener |
| PR 82 , 664 (1951) | 663 | 36.6 | On Gauge Invariance and Vacuum Polarization | J. Schwinger |
| PR 100 , 545 (1955) | 350 | 41.9 | Neutron Diffraction Study of the Magnetic Properties of the Series of Perovskite-Type Compounds [(1 - <i>x</i>)La, <i>x</i> Ca]MnO ₃ | E. O. Wollan, W. C. Koehler |
| PR 100 , 564 (1955) | 275 | 42.0 | Theory of the Role of Covalence in the Perovskite-Type Manganites [La, M(II)]MnO ₃ | J. B. Goodenough |
| PR 100 , 675 (1955) | 461 | 43.2 | Considerations on Double Exchange | P. W. Anderson, H. Hasegawa |
| PR 109 , 1492 (1958) | 871 | 32.0 | Absence of Diffusion in Certain Random Lattices | P. W. Anderson |
| PR 115 , 485 (1959) | 484 | 32.4 | Significance of Electromagnetic Potentials in the Quantum Theory | Y. Aharonov, D. Bohm |
| PR 118 , 141 (1960) | 500 | 37.1 | Effects of Double Exchange in Magnetic Crystals | P.-G. de Gennes |

TABLE III: The 11 discovery papers, as defined in the text, arranged chronologically. *PR*, *Physical Review*; *PRA*, *Physical Review A*; *PRB*, *Physical Review B*; *PRD*, *Physical Review D*; *PRL*, *Physical Review Letters*.

| Publication | # cites | Av. Age | Title | Author(s) |
|-----------------------------|---------|---------|--|--|
| PR 125 , 1067 (1962) | 587 | 7.0 | Symmetries of Baryons and Mesons | M. Gell-Mann |
| PR 182 , 1190 (1969) | 563 | 13.8 | Nucleon-Nucleus Optical-Model Parameters, $A > 40$, $E < 50$ MeV | F. D. Becchetti, Jr., G. W. Greenlees |
| PRD 2 , 1285 (1970) | 738 | 11.2 | Weak Interactions with Lepton-Hadron Symmetry | S. L. Glashow, J. Iliopoulos, L. Maiani |
| PRL 32 , 438 (1974) | 545 | 11.1 | Unity of All Elementary Forces | H. Georgi, S. L. Glashow |
| PRD 10 , 2445 (1974) | 577 | 11.9 | Confinement of Quarks | K. G. Wilson |
| PRD 12 , 147 (1975) | 501 | 10.7 | Hadron Masses in a Gauge Theory | A. De Rújula, H. Georgi, S. L. Glashow |
| PRL 53 , 1951 (1984) | 559 | 7.9 | Metallic Phase with Long-Range Orientational Order and No Translational Symmetry | D. Shechtman, I. Blech, D. Gratias, J. W. Cahn |
| PRA 33 , 1141 (1986) | 501 | 6.4 | Fractal Measures and Their Singularities: The Characterization of Strange Sets | T. C. Halsey et al. |
| PRL 58 , 908 (1987) | 625 | 1.9 | Superconductivity at 93 K in a New Mixed-Phase Yb-Ba-Cu-O Compound System at Ambient Pressure | M. K. Wu et al. |
| PRL 58 , 2794 (1987) | 525 | 4.8 | Theory of high- T_c Superconductivity in Oxides | V. J. Emery |
| PRB 43 , 130 (1991) | 677 | 5.2 | Thermal Fluctuations, Quenched Disorder, Phase Transitions, and Transport in Type-II Superconductors | D. S. Fisher, M. P. A. Fisher, D. A. Huse |

TABLE IV: The 10 hot papers, as defined in the text, arranged chronologically. *PR*, *Physical Review*; *PRB*, *Physical Review B*; *PRL*, *Physical Review Letters*.

| Publication | # cites | Av. Age | Title | Author(s) |
|------------------------------|---------|---------|--|--|
| PR 40 , 749 (1932) | 561 | 55.8 | On the Quantum Correction... | E. Wigner |
| PR 47 , 777 (1935) | 492 | 59.6 | Can Quantum-Mechanical Description... | A. Einstein, B. Podolsky, N. Rosen |
| PR 109 , 1492 (1958) | 871 | 32.0 | Absence of Diffusion in Certain Random Lattices | P. W. Anderson |
| PR 136 , B864 (1964) | 2460 | 28.7 | Inhomogeneous Electron Gas | P. Hohenberg, W. Kohn |
| PR 140 , A1133 (1965) | 3227 | 26.6 | Self-Consistent Equations Including Exchange... | W. Kohn, L. J. Sham |
| PRB 13 , 5188 (1976) | 1023 | 20.8 | Special Points for Brillouin-Zone Integrations | H. J. Monkhorst, J. D. Pack |
| PRL 48 , 1425 (1982) | 829 | 15.1 | Efficacious Form for Model Pseudopotentials | L. Kleinman, D. M. Bylander |
| PRB 41 , 7892 (1990) | 691 | 9.7 | Soft Self-Consistent Pseudopotentials in a Generalized Eigenvalue Formalism | D. Vanderbilt |
| PRB 45 , 13244 (1992) | 394 | 8.1 | Accurate and Simple Analytic Representation of the Electron-Gas Correlation Energy | J. P. Perdew, Y. Wang |
| PRL 70 , 1895 (1993) | 495 | 7.4 | Teleporting an Unknown Quantum State via Dual Classical and EPR Channels | C. H. Bennett, G. Brassard, C. Crépeau, R. Jozsa, A. Peres, W. K. Wootters |

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