Citation Statistics From More Than a Century of Physical Review

S. Redner[1,*]

[1] *Center for BioDynamics, Center for Polymer Studies, and Department of Physics, Boston University, Boston, MA, 02215*

We study the statistics of citations from all Physical Review journals for the 110-year period 1893 until 2003. In addition to characterizing the citation distribution and identifying publications with the highest citation impact, we investigate how citations evolve with time. There is a positive correlation between the number of citations to a paper and the average age of citations. Citations *from* a publication have an exponentially decaying age distribution; that is, old papers tend to not get cited. In contrast, the citations *to* a publication are consistent with a power-law age distribution, with an exponent close to -1 over a time range of $2-20$ years. We also identify a number of strongly-correlated citation bursts and other dramatic features in the time history of citations to individual publications.

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I. INTRODUCTION

In this article, we study quantitative features of the complete set of citations for all publications in Physical Review (PR) journals from the start of the journal in July 1893 until June 2003 [1]. This corpus provides a comprehensive dataset from which we can learn many interesting statistical facts about scientific citations. An especially useful aspect of this data is that it encompasses a continuous span of 110 years, and thus provides a broad window with which to examine the time evolution of citations and the citation history of individual publications.

The quantitative study of citations has a long history in bibliometrics, a subfield of library and information science (see *e.g.,* [2] for a general introduction and [3–5] for leads into this literature). The first study of citations by physicists was apparently made by Price [6], in which he built upon the original Simon model [7] to conclude that the distribution of citations had a power-law form. It is also worth mentioning much earlier work by Lotka [8] and by Shockley [9] on the distribution of the number of publications by individual scientists. In the context of citations, Price termed the mechanism for a power-law citation distribution as cumulative advantage, in that that rate at which a paper gets cited could be expected to be proportional to its current number of citations. This mechanism is now known as preferential attachment [10] in the framework of growing network models.

Recently, larger studies of citation statistics were performed that made use of datasets that became available from the Institute for Scientific Information (ISI) [11] and from the SPIRES database [12]. Based on data for top-cited authors, the citation distribution for individuals was argued to have a stretched exponential form [13]. On the other hand, by analyzing a dataset of 783,339 papers from all ISI-cataloged journals and all 24,296 papers in Physical Review D from 1975 until 1994, a power-law citation distribution was inferred [14], with an exponent of -3 that coincided with subsequent predictions from idealized networks that grow by preferential attachment [10, 15–17]. This result was also in accord with the original expectation from Price's original work [6]. Finally, it is worth mentioning two current statistical studies of collaborations among authors that are based on a diverse set of articles from MEDLINE, arXiv.org, NCSTRL, and SPIRES [18], and set of mathematics and neuroscience articles [19].

This work is focused on the citation statistics of individual articles. While the total number of PR citations contained in our study is less than half of what was previously considered in Ref. [14] (approximately 3.1 million vs. 6.7 million), the new data encompasses 110 years of citations from what is arguably the most prominent set of archival physics journals after 1945. Thus we are able to uncover a variety of new features associated with the time history of citations. These include highly correlated bursts of citations, well-defined trends, and, conversely, downturns in research activity.

It is important to be aware that citation data from a single journal, even one as central as Physical Review, has significant omissions. As we shall discuss in the concluding section, the ratio of the number of internal citations (cites to a PR papers by other PR publications; this dataset) to total citations (cites to a PR paper by all publications) is as small as $1/5$ for well-cited elementary-particle physics publications. It is reasonable to expect that a similar ratio of internal to total citations also occurs for typical PR publications. The existence of so many citations from publications outside PR journals could alter some of the generic citation histories that we shall present.

There are also many famous papers that did not appear in PR journals, as well as highly-cited authors that typically did not publish in PR journals. This tension between PR and non-PR journals has been influenced by global socioeconomic factors, as well as, more recently, by opportunistic considerations, such as changes in page charge policies and the creation of electronic archives and

*Electronic address: `redner@bu.edu`

electronic journals. All these factors serve to caution the reader that the primary observations of this study are only a partial glimpse into the true citation impact of physics research publications.

II. CITATION DATA

A. General Facts

The data provided by the Physical Review Editorial Office covers the period 1893 (the start of the journal) through June 30, 2003. The data is in the following list form (with PRB = Phys. Rev. B, PRE = Phys. Rev. E, PRL = Phys. Rev. Lett., RMP = Rev. Mod. Phys., etc.) [20]:

PRB 19 1203 1979 | PRB 20 4044 1979
PRB 19 1203 1979 | PRB 22 1096 1980
PRB 19 1213 1979 | PRB 27 380 1983
PRB 19 1225 1979 | PRB 24 714 1981
PRB 19 1225 1979 | PRL 55 2991 1985
PRB 19 1225 1979 | PRB 38 3075 1988
PRB 19 1225 1979 | RMP 63 63 1991
PRB 19 1225 1979 | PRE 62 6989 2000

To the left of the vertical line is the *cited* paper and to the right is the *citing* paper. In the above sample, Phys. Rev. B **19**, 1225 (1979) was cited 5 times, once each in 1981, 1985, 1988, 1991, and 2000. There are 3,110,839 citations in the complete data set and the number of distinct publications that have at least one citation is 329,847. There are a total of 353,268 publications [21], so that only 6.6% of all PR publications are uncited; this is much smaller than the 47% fraction of uncited papers in the ISI dataset [14]. The average number of citations for all PR publications is 8.806. We emphasize again that this dataset does not include citations to or from papers outside of PR journals.

There are a variety of amusing basic facts about this citation data. 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

For studying the time history of citations, we define the age of a citation as the difference in the year that a citation occurred and the publication year of the cited paper. For all PR publications, the average citation age in 6.2 years. On the other hand, for papers with more than 100 citations, the average citation age is 11.7 years. The average age climbs to 14.6 years for publications with more than 300 citations and 18.9 years for the 11 publications with more than 1000 citations. As one might expect, highly-cited papers are long-lived. Conversely, for papers with only young citations, the number of citations is typically small. For example, for publications (before 2000) in which the average citation age is less than 2 years, the average number of citations is 3.55.

B. Accuracy

Because citation data is larger generated by individual authors, a natural concern is accuracy of this data. In recent years, cross-checking mechanisms have been instituted by the Physical Review Editorial Office to promote accuracy. In older papers, however, a variety of citation errors exist [22]. One can get a sense of their magnitude by looking at the reference lists of old PR papers in the on-line PR journals (prola.aps.org). References to PR papers that are not hyperlinked typically are erroneous (exceptions are citations to proceedings of old APS meetings, where the page of the cited article generally does not match the hyperlinked first page of the proceedings section). By scanning through a representative set of publications, one will see that such citations are occasional but not rare.

While author-generated citation errors, caused by carelessness or propagation of erroneous citations, are hard to detect systematically, the following types of errors are easily determined:

1. Old citations are potentially suspect. A typical example occurs when author(s) meant to cite, for example, Phys. Rev. B **2**, xxx (1970), but instead cited Phys. Rev. **2**, xxx (1913). There are 14807 citations older than 50 years in the initial dataset, with 4734 of these to a publication with a single citation, a feature that suggests an erroneous citation. By looking every hundredth of these 4734 citations, 39 out of 47 ($\approx 83\%$) were in fact incorrect. The accuracy rate improves to approximately 50% for the 606 papers with 2 citations and presumably becomes progressively more accurate for publications with a larger number of citations.

2. Citations to pages beyond the total number of pages in the cited volume. This type of error partially overlaps with item 1. In vols. 1–80 of Phys. Rev. (until 1950), there are 4152 such errors out of 125,240 citations. In vols. 1–85 for PRL (for which conventional page numbers are used), there are 2777 beyond-page errors out of 912,394 citations, with more recent citations being progressively more accurate. For example, there are only 11 beyond-page errors in vols. 80–85, while there are 145 such errors in vol. 23 alone.

3. Acausal citations; that is, a citation to a publication in the future. There are 1102 such errors.

4. Truncated page numbers. In PR issues after 2001, papers are identified by a six-digit number that be-

gins with a leading "0", rather than a conventional page number. This leading digit was sometime not included.

5. Page numbers in vols. 133–139 of Phys. Rev. were prepended by an A or B, a convention that fostered citation errors (see Sec. IV on most-cited papers).

6. Two papers were referred to at once, *e.g.*, PRL **33**, 100, 300, (1990) when the lazy authors should have cited PRL **33**, 100, (1990) and PRL **33**, 300 (1990).

Additionally, there were easily-correctable mechanical defects in the original data. These include:

1. For volumes in which number of journal pages exceeded 10,000, the comma in the page number sometimes appeared as a non-standard character. The number of such errors was approximately 10,000.

2. Some lines contained either html or related markup language, or other unusual characters.

3. Annotated page numbers. For example, citations to the same paper could appear as PRE **10**, 100 (1990) and PRE **10**, 100(R) (1990). Annotations included (a), A, (A), (b), B, (B), (BR), (e), E, (E), L, (L), R, (R), [R], (T), (3), (5). Many have clear meanings (letter, erratum, as well as (A), A, and (a) for meeting notes in the early APS years), while other seem to be meaningless. The number of such lines was approximately 1500.

In summary, the number of "obvious" author-generated citation errors that could be identified in an automated matter is of the order of 10,000, an error rate of approximately $\frac{1}{3}$%. The number of non-obvious errors, *i.e.*, citations where the volume, page number, and publication year are not manifestly wrong, is likely much higher. However, upon perusal of subsets of the data, it appears that the total error rate is of the order of a few percent, and is considerably smaller in recent years, even as the overall publication rate has increased. With these caveats, we now analyze the citation data to learn basic features of the citation distribution and related quantities.

III. THE CITATION DISTRIBUTION

One basic aspect of citations is their rapid growth in time (Fig. 1), a feature that mirrors the growth of PR journals themselves. This growth needs to be accounted for in any realistic modeling of the distribution of scientific citations (see *e.g.*, [23]). The number of citations by *citing* papers published in a given year is shown as the dashed curve, and the number of citations to *cited* papers that were published in a given year is shown as the solid curve. Notice the significant drop in citations during the period of World War II. The fact that the two curves are so closely correlated during WWII (and indeed throughout most of the past century) indicates that most citations are to very recent papers. Another noteworthy feature is that the long-term growth rate of citations is smaller after WWII than before. The very recent decay in cited publications occurs because such papers have not yet sufficient time to be completely cited. Finally, notice also that area under the two curves must be the same.

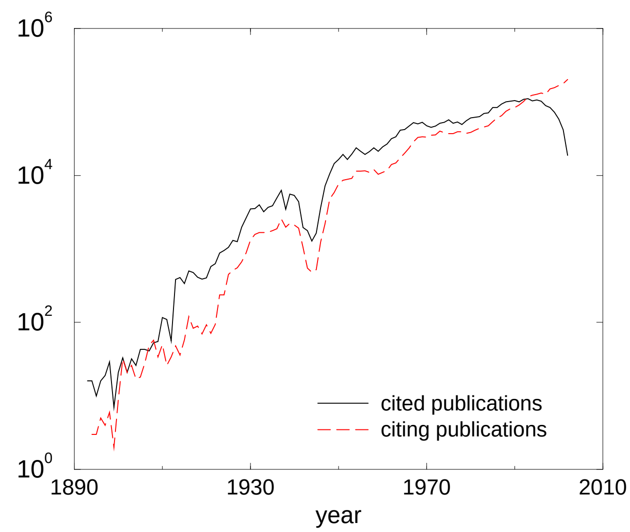

FIG. 1: Total number of PR citations by year.

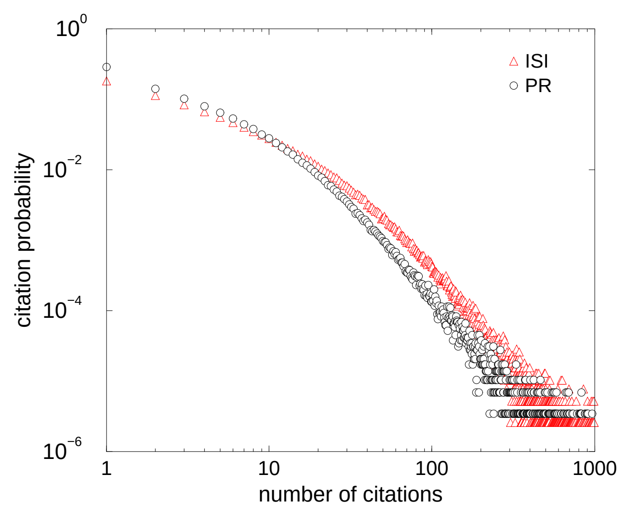

FIG. 2: Normalized citation distributions for all papers in Phys. Rev. from 1893 to 2003 (○) and from the ISI dataset (Δ). The latter include papers published in 1981 that were cited between 1981 and 1997 (from Ref. [14]).

We next show the citation distribution for the entire dataset (Fig. 2). This distribution is visually similar to that in Ref. [14] for the corresponding ISI distribution.

While there is systematic curvature in the data on a double logarithmic scale, a Zipf plot of the ISI data, which focuses on the large-citation tail, suggested a power-law form for the citation distribution [14]. A similar conclusion for the citation distribution can thus be expected for the PR data. A straightforward power-law fit to the data in the range of $50 - 300$ citations gives an exponent of -2.55 for both the PR and ISI data; however, as argued in Ref. [14] by using a Zipf plot, the exponent of the ISI citation distribution is consistent with the value -3

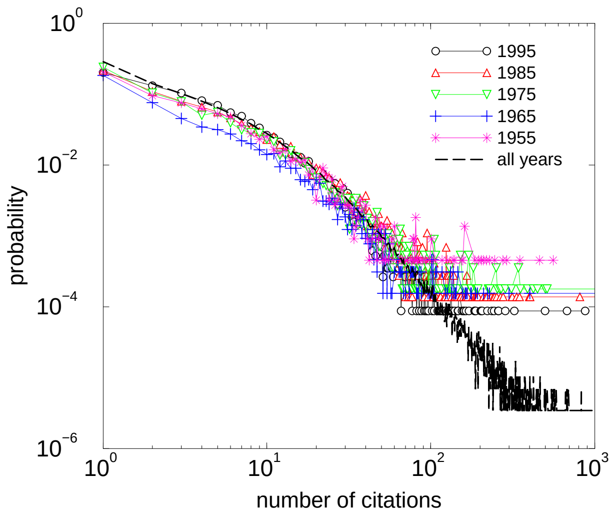

FIG. 3: Normalized citation distributions in selected years.

To check if the nature of the citation distribution is affected by the growth of PR journals, we plot in Fig. 3 the normalized citation distribution to papers published in selected years, along with the normalized total citation distribution. We see that these yearly distributions closely match the total distribution except at the large-citation tail. There is also a hint that the form of the citation distribution for small number of citations ($\lesssim 20$) is qualitatively different than the rest of the distribution. A natural suspicion is that self-citations might play a significant role because papers with few citations are likely to be predominantly self-cited.

IV. RANKING BY CITATION IMPACT

One feature of citations that attracts general interest is the identity of highly-cited papers. To decide on which papers are most influential, we argue that a ranking based on only the number of citations does not distinguish between publications that are heavily cited for a short period and those cited over many decades. While the former history might arise from major discoveries, it could also arise from incorrect results, transitory subjects, or papers that are "first to be second" in a field. Thus a more useful measure of the impact of a publication should involve both the number of citations to a publication and the average age of these citations. We define the product of these two quantities as the citation impact of a paper.

A top-100 list based on this citation impact ranking is given below. Also tabulated are the number of citations to each publication and the average age of these citations, with both measures determined as of June 2003. The earliest paper on this list was published in 1929 and the most recent in 1986. By decades, the number of papers in the top-100 list are: (1920's – 1, 1930's – 10, 1940's – 9, 1950's – 28, 1960's – 30, 1970's – 13, and 1980's – 9). There are two individuals who have co-authored five papers on this top-100 list: W. Kohn, who occupies positions 1, 2, 24, 96, and 100, and P. W. Anderson (positions 9, 19, 20, 35, & 41). Papers by E. P. Wigner appear four times (4, 8, 53, & 55), and papers by L. Onsager (16, 64, & 68) and by J. C. Slater (12, 27, & 40) each appear three times. Individuals with two publications include J. Bardeen, C. P. Bean, R. H. Dicke, R. J. Glauber, D. R. Hamann, P. Hohenberg, J. M. Luttinger, Y. Nambu, E. M. Purcell, M. Schlüter, J. Schwinger, G. H. Wannier, and J. A. Wheeler.

TABLE I: Top-100 articles ranked by citation impact.

Impact Rank	Publication				# cites	Av. Age	Impact	Title	Author(s)
1	PR	140	A1133	1965	3227*	26.64	85972	Self-Consistent Equations...	W. Kohn & L. J. Sham
2	PR	136	B864	1964	2460*	28.70	70604	Inhomogeneous Electron Gas	P. Hohenberg & W. Kohn
3	PR	124	1866	1961	1178	27.97	32949	Effects of Configuration...	U. Fano
4	PR	40	749	1932	561	55.76	31281	On the Quantum Correction...	E. Wigner
5	PRB	23	5048	1981	2079	14.38	29896	Self-Interaction Correction to...	J. P. Perdew & A. Zunger
6	PR	82	403	1951	643	46.35	29803	Interaction Between d-Shells ..	C. Zener
7	PR	47	777	1935	492	59.64	29343	Can Quantum-Mechanical Description of Physical ..	A. Einstein, B. Podolsky, & N. Rosen
8	PR	46	1002	1934	557	51.49	28680	On the Interaction of Electrons...	E. Wigner
9	PR	109	1492	1958	871	32.00	27872	Absence of Diffusion in...	P. W. Anderson
10	PR	108	1175	1957	1364	20.18	27526	Theory of Superconductivity	J. Bardeen, L. N. Cooper, & J. R. Schrieffer

TABLE I: continued from previous page

Impact Rank	Publication				# cites	Av. Age	Impact	Title	Author(s)
11	PRL	45	566	1980	1781	15.42	27463	Ground State of the Electron ...	D. M. Ceperley & B. J. Alder
12	PR	94	1498	1954	781	32.69	25531	Simplified LCAO Method for...	J. C. Slater & G. F. Koster
13	PR	82	664	1951	663	36.60	24266	On Gauge Invariance and...	J. Schwinger
14	PRB	12	3060	1975	1259	18.35	23103	Linear Methods in Band Theory	O. K. Andersen
15	RMP	15	1	1943	568	40.14	22800	Stochastic Problems in...	S. Chandrasekhar
16	PR	65	117	1944	568	40.13	22794	Crystal Statistics	L. Onsager
17	PRB	13	5188	1976	1023	20.75	21227	Special Points for Brillouin-Zone	H. J. Monkhorst & J. D. Pack
18	PRL	19	1264	1967	1306	15.46	20191	A Model of Leptons	S. Weinberg
19	PR	100	675	1955	461	43.22	19924	Considerations on Double...	P. W. Anderson & H. Hasegawa
20	PR	124	41	1961	819	22.85	18714	Localized Magnetic States...	P. W. Anderson
21	PR	118	141	1960	500	37.10	18550	Effects of Double Exchange...	P.-G. de Gennes
22	PR	122	345	1961	683	26.45	18065	Dynamical Model of Elementary...	I. Y. Nambu & G. Jona-Lasinio
23	PR	56	340	1939	342	49.29	16857	Forces in Molecules	R. P. Feynman
24	PR	97	869	1955	559	29.49	16485	Motion of Electrons and Holes in...	J. M. Luttinger & W. Kohn
25	PR	115	485	1959	484	32.35	15657	Significance of Electromagnetic...	Y. Aharonov & D. Bohm
26	PR	131	2766	1963	727	21.53	15652	Coherent and Incoherent...	R. J. Glauber
27	PR	81	385	1951	583	26.19	15269	A Simplification of the Hartree-...	J. C. Slater
28	PRL	17	1133	1966	648	23.56	15267	Absence of Ferromagnetism...	N. D. Mermin & H. Wagner
29	PR	93	99	1954	473	31.99	15131	Coherence in Spontaneous...	R. H. Dicke
30	PR	100	545	1955	350	41.90	14665	Neutron Diffraction Study of...	E. O. Wollan & W. C. Koehler
31	RMP	49	435	1977	910	15.50	14105	Theory of Dynamic Critical...	P. C. Hohenberg & B. I. Halperin
32	PR	102	1030	1956	449	29.80	13380	Quantum Theory of Cyclotron...	J. M. Luttinger
33	PRL	20	1445	1968	552	23.91	13198	Absence of Mott Transition	E. H. Lieb & F. Y. Wu
34	PR	58	1098	1940	329	40.08	13186	Field Dependence of...	T. Holstein & H. Primakoff
35	PRL	42	673	1979	965	12.98	12526	Scaling Theory of Localization:	E. Abrahams et al.
36	PRL	48	1425	1982	829	15.05	12477	Efficacious Form for ...	L. Kleinman & D. M. Bylander
37	PR	100	564	1955	275	42.02	11556	Theory of the Role of Covalence	J. B. Goodenough
38	PRB	8	5747	1973	642	17.86	11466	Special Points in the Brillouin...	D. J. Chadi & M. L. Cohen
39	RMP	54	437	1982	1045	10.82	11307	Electronic Properties of...	T. Ando, A. B. Fowler, & F. Stern
40	PR	36	57	1930	294	38.42	11296	Atomic Shielding Constants	J. C. Slater
41	PR	86	694	1952	336	33.45	11239	An Approximate Quantum...	P. W. Anderson
42	PR	96	99	1954	444	24.79	11007	Indirect Exchange Coupling of...	M. A. Ruderman & C. Kittel
43	PRL	10	531	1963	574	19.05	10935	Unitary Symmetry and Leptonic...	N. Cabibbo
44	PR	139	A796	1965	416*	26.23	10913	New Method for Calculating...	L. Hedin
45	PR	167	331	1968	691	15.72	10863	Transition Temperature of...	W. L. McMillan
46	RMP	21	392	1949	275	39.45	10849	Forms of Relativistic Dynamics	P. A. M. Dirac
47	PR	84	1232	1951	381	27.78	10584	A Relativistic Equation for...	E. E. Salpeter & H. A. Bethe
48	PR	34	57	1929	216	48.99	10582	Diatomic Molecules According...	P. M. Morse
49	PRB	26	4199	1982	830	12.63	10483	Pseudopotentials That Work:...	G. B. Bachelet, D. R. Hamann, & M. Schlüter
50	PR	145	637	1966	427	24.25	10355	Effect of Invariance...	P. N. Keating
51	PR	73	679	1948	423	23.93	10122	Relaxation Effects...	N. Bloembergen, E. M. Purcell, & R. V. Pound
52	PRD	17	2369	1978	583	17.25	10057	Neutrino Oscillations in Matter	L. Wolfenstein
53	PR	73	1002	1948	288	34.58	9959.0	On the Behavior of...	E. P. Wigner
54	RMP	30	257	1958	465	21.41	9955.7	R-Matrix Theory of ...	A. M. Lane & R. G. Thomas
55	PR	50	58	1936	276	36.05	9949.8	Theory of Brillouin Zones...	L. P. Bouckaert, R. Smoluchowski, & E. Wigner
56	RMP	57	287	1985	1055	9.17	9674.4	Disordered Electronic Systems	P. A. Lee & T. V. Ramakrishnan
57	PR	69	681	1946	221	43.00	9503	Spontaneous Emission...	E. M. Purcell
58	PRL	8	250	1962	334	28.42	9492.3	Magnetization of Hard...	C. P. Bean
59	PR	73	360	1948	230	40.75	9372.5	The Influence of Retardation on ...	H. B. G. Casimir & D. Polder
60	PR	89	1102	1953	369	24.97	9213.9	Nuclear Constitution and...	D. L. Hill & J. A. Wheeler
61	PR	95	249	1954	392	23.38	9165.0	Correlations in Space and Time...	L. Van Hove
62	PR	74	1168	1948	396	23.13	9159.5	The Dipolar Broadening of...	J. H. Van Vleck
63	PRL	10	486	1963	319	28.47	9081.9	Tunneling Between...	V. Ambegaokar & A. Baratoff

TABLE I: continued from previous page

Impact Rank	Publication				# cites	Av. Age	Impact	Title	Author(s)
64	PR	37	405	1931	181	49.12	8890.7	Reciprocal Relations in... I.	L. Onsager
65	PRL	43	1494	1979	702	12.60	8845.2	Norm-Conserving Pseudo-potentials	D. R. Hamann, M. Schlüter, & C. Chiang
66	PR	147	392	1966	352	24.94	8778.9	Ferromagnetism in a Narrow...	Y. Nagaoka
67	PRD	10	275	1974	606	14.38	8714.3	Lepton Number as the Fourth...	J. C. Pati & A. Salam
68	PR	38	2265	1931	174	49.61	8632.1	Reciprocal Relations in.... II.	L. Onsager
69	PRD	7	1888	1973	593	14.35	8510.0	Radiative Corrections as the...	S. Coleman & E. Weinberg
70	PR	108	1384	1957	364	23.26	8466.6	Intensity of Optical Absorption...	R. J. Elliott
71	PRL	55	2471	1985	812	10.41	8452.9	Unified Approach for Molecular...	R. Car & M. Parrinello
72	PR	124	925	1961	310	26.86	8326.6	Mach's Principle and a...	C. Brans & R. H. Dicke
73	PRD	2	1285	1970	738	11.21	8273.0	Weak Interactions with Lepton-...	S. L. Glashow, J. Iliopoulos, & L. Maiani
74	PR	135	A640	1964	348*	23.77	8272.7	Linear Magnetic Chains with...	J. C. Bonner & M. E. Fisher
75	PR	124	246	1961	303	27.25	8256.8	Dynamical Model of Elementary...	Y. Nambu & G. Jona-Lasinio
76	PRD	9	3320	1974	523	15.74	8232.0	Symmetry Behavior at Finite...	L. Dolan & R. Jackiw
77	RMP	36	31	1964	283	28.82	8156.0	Magnetization of High-Field...	C. P. Bean
78	PR	140	A1197	1965	322*	25.29	8143.8	Theory of the Motion of Vortices...	J. Bardeen & M. J. Stephen
79	PR	177	2426	1969	519	15.56	8075.6	Axial-Vector Vertex in...	S. L. Adler
80	PRL	35	1399	1975	513	15.66	8033.6	Random-Field Instability of...	Y. Imry & S.-k. Ma
81	PR	80	580	1950	288	27.88	8029.4	Spin Echoes	E. L. Hahn
82	PR	130	2529	1963	361	22.20	8014.2	The Quantum Theory of Optical...	R. J. Glauber
83	PR	106	893	1957	385	20.69	7965.7	Magnetic Properties of Cu-Mn...	K. Yosida
84	PRB	13	4274	1976	542	14.61	7918.6	Exchange and Correlation in...	O. Gunnarsson & B. I. Lundqvist
85	PR	112	1555	1958	275	28.67	7884.3	...Contribution of Excitons...	J. J. Hopfield
86	PRL	56	889	1986	802	9.83	7883.7	Dynamic Scaling of Growing Interfaces	M. Kardar, G. Parisi, & Y.-C. Zhang
87	PRD	23	347	1981	676	11.62	7855.1	Inflationary Universe:...	A. H. Guth
88	PR	87	410	1952	236	33.08	7806.9	Statistical Theory of Equations...	T. D. Lee & C. N. Yang
89	PR	87	366	1952	335	23.28	7798.8	The Inelastic Scattering of...	W. Hauser & H. Feshbach
90	PRL	10	159	1963	273	28.56	7796.9	Effect of Correlation on...	M. C. Gutzwiller
91	PR	182	1190	1969	563	13.75	7741.3	Nucleon-Nucleus Optical-Model...	F. D. Becchetti Jr. & G. W. Greenlees
92	PR	56	426	1939	259	29.81	7720.8	The Mechanism of Nuclear Fission	N. Bohr & J. A. Wheeler
93	PR	90	817	1953	212	36.37	7710.4	The Threshold Law for...	G. H. Wannier
94	PR	124	287	1961	263	29.20	7679.6	Conservation Laws and...	G. Baym & L. P. Kadanoff
95	PRL	18	546	1967	339	22.43	7603.8	Polarizability of a Two-Dimensional Electron...	F. Stern
96	PR	123	1242	1961	236	31.97	7544.9	Cyclotron Resonance and...	W. Kohn
97	PR	52	191	1937	194	38.65	7498.0	The Structure of Electronic...	G. H. Wannier
98	PR	128	2425	1962	301	24.57	7395.6	Gauge Invariance and Mass. II	J. Schwinger
99	PR	81	988	1951	201	36.64	7364.6	A Theory of Cooperative...	R. Kikuchi
100	PR	94	1111	1954	280	26.15	7322.0	Solution of the Schroedinger...	W. Kohn & N. Rostoker

The entries with asterisks in Table I denote publications in those issues of PR with the prepended A or B on the page numbers. For these publications, the following citations had omitted the prepended A or B:

Phys. Rev. **140**, A1133 (1965): 123 out of 3227 total
Phys. Rev. **136**, B864 (1964): 120 out of 2640 total
Phys. Rev. **139**, A796 (1965): 14 out of 416 total
Phys. Rev. **135**, A640 (1964): 19 out of 348 total
Phys. Rev. **140**, A1197 (1964): 21 out of 322 total

Our use of citation impact as the criterion for a top-100 list, handicaps more recent highly-cited publications, where the citation age is necessarily small. We therefore provide below all the remaining 33 PR publications with more than 500 citations that did not qualify for the initial top-100 list. The citation rank of each of these publications is also given. In addition to tabulating citations up to June 2003, we also provide the citations as of June 2004. There is a wide variation in the current rate of citations; while one publication has a single citation in the past year, another has more than 150. Based on these citation rates, several of the articles listed here should soon displace publications in the initial top-100 list.

TABLE II: The remaining PR publications with more than 500 citations.

Cite Rank	Publication				# cites < 6/03	# cites < 6/04	Av. Age	Impact	Title	Author(s)
14	RMP	66	1125	1994	899	969	4.78	4297.2	Vortices in High-Temperature...	G. Blatter et al.
15	PRB	43	1993	1991	892	1058	7.67	6841.7	Efficient Pseudopotentials for...	N. Troullier & J. L. Martins
16	PRL	75	3969	1995	874	926	4.33	3784.4	Bose-Einstein Condensation in...	K. B. Davis et al.
20	RMP	65	851	1993	829	899	5.52	4576.1	Pattern Formation Outside of...	M. C. Cross & P. C. Hohenberg
21	PRD	54	1	1996	826	836	2.22	1833.7	Review of Particle Physics	R. M. Barnett et al.
28	PRB	37	3759	1988	704	723	6.41	4512.6	Effective Hamiltonian for...	F. C. Zhang & T. M. Rice
30	PRL	59	381	1987	699	729	9.58	6696.4	Self-Organized Criticality:...	P. Bak, C. Tang, & K. Wiesenfeld
31	PRB	41	7892	1990	691	876	9.68	6689.0	Soft Self-Consistent Pseudopotentials in a Generalized...	D. Vanderbilt
34	PRL	47	1400	1981	680	702	10.57	7187.6	Diffusion-Limited Aggregation,...	T. A. Witten, Jr. & L. M. Sander
35	PRB	43	130	1991	677	710	5.17	3500.1	Thermal Fluctuations, Quenched Disorder, Phase Transitions,...	D. S. Fisher, M. P. A. Fisher, & D. A. Huse
36	PRL	75	1687	1995	677	715	4.24	2870.5	Evidence of Bose-Einstein Condensation in and Atomic Gas...	C. C. Bradley, C. A. Sackett, J. J. Tollett, & R. G. Hulet
39	RMP	58	801	1986	663	700	8.76	5807.9	Spin Glasses:...	K. Binder & A. P. Young
40	PRL	50	1395	1983	662	712	10.17	6732.5	Anomalous Quantum Hall:...	R. B. Laughlin
44	PRL	58	908	1987	625	629	1.94	1212.5	Superconductivity at 93 K...	M. K. Wu et al
45	PRD	50	1173	1994	623	624	2.19	1364.4	Review of Particle Properties	L. Montanet et al.
46	PRB	46	6671	1992	622	741	7.03	4372.7	Atoms, Molecules, Solids, and...	J. P. Perdew et al.
49	PR	125	1067	1962	587	590	7.02	4120.7	Symmetries of Baryons and...	M. Gell-Mann
52	PRD	10	2445	1974	577	604	11.90	6866.3	Confinement of Quarks	K. G. Wilson
53	PRL	77	3865	1996	575	805	4.83	2777.3	Generalized Gradient Approximation Made Simple	J. P. Perdew, K. Burke, & M. Ernzerhof
57	PRL	50	1153	1983	567	590	12.60	7144.2	Nonlinear Field Theory of...	F. D. M. Haldane
61	PRL	53	1951	1984	559	578	7.89	4410.5	Metallic Phase with Long-Range Orientational Order and...	D. Shechtman, I. Blech, D. Gratias, & J. W. Cahn
63	PRC	21	861	1980	557	568	12.01	6689.6	Parametrization of the Paris...	M. Lacombe et al.
65	PRL	32	438	1974	545	558	11.14	6071.3	Unity of All Elementary-...	H. Georgi & S. L. Glashow
66	RMP	64	1045	1992	545	631	6.66	3629.7	Iterative Minimization...	M. C. Payne et al.
68	PRL	61	2472	1988	535	585	8.67	4638.5	Giant Magnetoresistance...	M. N. Baibich et al.
69	PRB	16	1217	1977	533	548	11.88	6332.1	Renormalization, Vortices, and Symmetry-Breaking...	J. V. José, L. P. Kadanoff, S. Kirkpatrick, & D. R. Nelson
70	PRB	19	2457	1979	527	542	12.24	6450.5	Dislocation-Mediated Melting...	D. R. Nelson & B. I. Halperin
71	PRL	58	2794	1987	525	530	4.77	2504.3	Theory of High-T_c...	V. J. Emery
74	PRB	22	2099	1980	518	530	10.03	5195.5	Soliton Excitations in Polyacetylene	W. P. Su, J. R. Schrieffer, & A. J. Heeger
76	PRD	45	S1	1992	513	515	2.06	1056.8	Review of Particle Properties	Particle Data Group
77	PRL	42	1698	1979	502	522	10.99	5517.0	Solitons in Polyacetylene	W. P. Su, J. R. Schrieffer, & A. J. Heeger
78	PRA	33	1141	1986	501	513	6.44	3226.4	Fractal Measures and...	T. C. Halsey et al.
79	PRD	12	147	1975	501	518	10.66	5340.7	Hadron Masses in a Gauge Theory	A. De Rújula, H. Georgi, & S. L. Glashow

V. CITATION HISTORY

The citation histories of well-cited publications show a variety of intriguing features. As mentioned in Sec. II, a paper generally needs to have a long lifetime to be highly cited. Exceptions to this pattern have arisen in recent years, and appear to be fueled, in part, by more rapid dissemination of results and by an increased propensity for trend-following behavior. The most prominent example is the field of high-temperature superconductivity, where several highly-cited publications from the late 80's were cited more than 500 times within five years.

Another basic fact is that the citation histories of highly-cited papers are extremely diverse. Several illustrative and generic examples are shown in Figs. 4 & 5. The paper with most citations in all PR journals is "Self-Consistent Equations Including Exchange and Correlation Effects", Phys. Rev. **140**, A1133 (1965) by W. Kohn & L. J. Sham (KS), with 3227 citations as of June 2003. It is amazing that citations to this publication have been steadily increasing for nearly 40 years. Another noteworthy example is "Interaction between the d-Shells in the Transition Metals. II. Ferromagnetic Compounds of Manganese with Perovskite Structure", Phys. Rev. **82**, 403 (1951), by C. Zener (Z). Although this paper has "only" 678 citations through the end of 2003, the bulk of its citations occurred nearly 50 years after publication! The citation spike around the year 2000 is a consequence of a resurgence of interest in colossal magnetoresistance, to be discussed in more detail in Sec. VII.

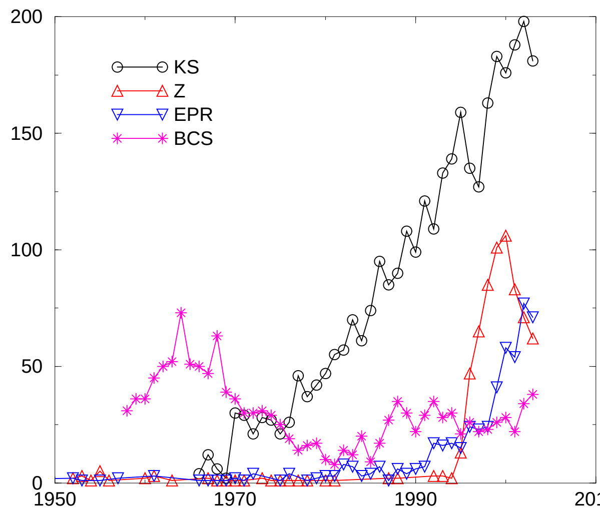

FIG. 4: Citation history of four classic highly-cited publications. Each is identified by author initials (see text).

Shown also are the citation histories of "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?", Phys. Rev. **47**, 777 (1935) by A. Einstein, B. Podolsky, & N. Rosen (EPR) and "Theory of Superconductivity", Phys. Rev. **108**, 1175 (1957) by J. Bardeen, L. N. Cooper, & J. R. Schrieffer (BCS). EPR had 82 citations before 1990 and 515 citations subsequently – 597 citations in total at the end of 2003. The longevity of EPR is the reason for the appearance of this publication on the top-100 citation impact list. The current interest in EPR stems from the revival of work on quantum information phenomena (see Sec. VII). In a similar vein, the citation history of BCS peaked in the 60's, followed by a steady decay through the mid-80's, with a minimum in the number of citations in 1985, the year before the discovery of high-temperature superconductivity. It is worth emphasizing that BCS is the first

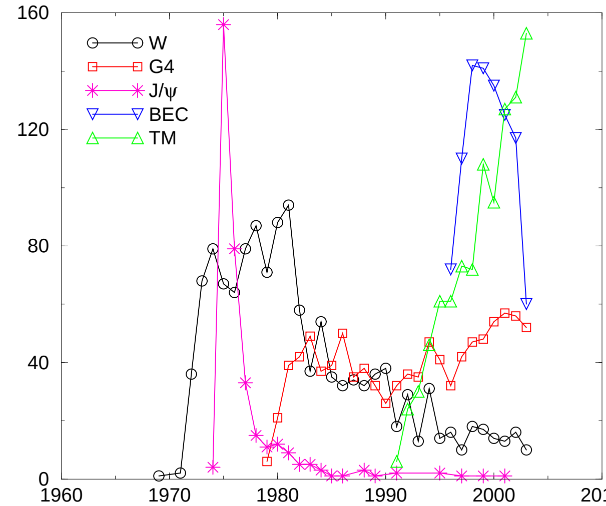

FIG. 5: Citation history of six, more recent highly-cited publications identified by author initials or by topic (see text).

PR publication with more than 1000 citations (with 1388 citations at the end of 2003).

Fig. 5 illustrates the diversity of citation histories for several more recent publications. The paper, "A Model of Leptons", Phys. Rev. Lett. **19**, 1264 (1967), by S. Weinberg, was a major advance in the electroweak theory (1311 citations at the end of 2003; #18 in impact rank), and the citation history follows what one might naively anticipate – a peak, as befitting a major discovery, followed by a slow decay. Parenthetically, the same citation history occurs for the related paper "Weak Interactions with Lepton-Hadron Symmetry", Phys. Rev. D **2**, 1285 (1970) by S. L. Glashow, J. Iliopoulos, & L. Maiani (742 citations at the end of 2003; #73 in impact rank). In contrast, "Scaling Theory of Localization: Absence of Quantum Diffusion in Two Dimensions", Phys. Rev. Lett. **42**, 673 (1979) by E. Abrahams, P. W. Anderson, D. C. Licciardello, & T. V. Ramakrishnan (the "gang of four", G4; #35 in impact rank) has been cited between 40 - 60 times nearly every year since publication. Given the seminal nature and the ensuing research spawned by these three publications, it is paradoxical that the rate of citations to the former two have decayed so significantly.

Another set of amusing examples include the two publications that announced the discovery of the J/ψ particle – Phys. Rev. Lett. **33**, 1404 & 1406 (1974). The citation histories of these two publications are essentially identical and could only be characterized as supernovae. The publication "Bose-Einstein Condensation in a Gas of Sodium Atoms", Phys. Rev. Lett. **75**, 3969 (1995) by K. B. Davis, M.-O. Mewes, M. R. Andrews, N. J. van Druten, D. S. Durfee, D. M. Kurn, & W. Ketterle (BEC) also has a strongly-peaked citation history (but less extreme than the J/ψ papers), as befits an important discovery in a quickly evolving field. Many well-recognized papers that report major discoveries have such a sharply-peaked citation history.

Finally, we show the citation history of "Efficient Pseudopotentials for Plane-Wave Calculations", Phys. Rev. B **43**, 1993 (1991) by N. Troullier & J. L. Martins (TM). This publication has the same citation pattern as the Kohn-Sham paper, but with a compressed time scale and an amplified citation scale. Based on its past decade of citations, this paper appears destined to have a significant citation impact. Several more examples of this exception type of citation pattern will be identified and discussed in Sec. VII.

VI. AGE CHARACTERISTICS OF CITATIONS

One of the more useful aspects of having 110 years of citation data is the ability to study their age structure. In theoretical modeling of growing networks, it was found that the combined age-degree distribution of the nodes in a network provide many useful structural insights about networks [17, 24]. Here, the degree of a node – the number of links attached to this node – plays the role of the number of citations in the underlying citation network.

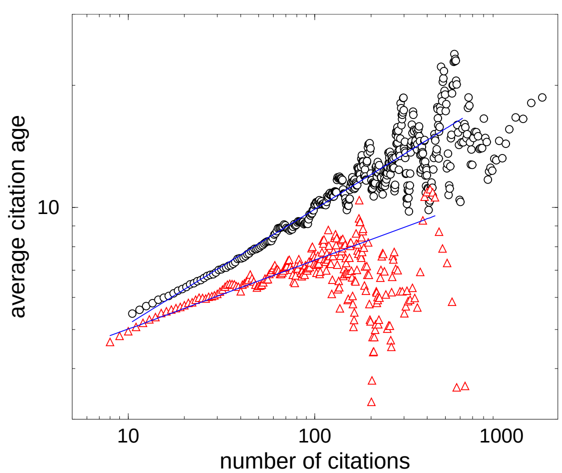

FIG. 6: Average age of citations to a given paper versus number of citations to this paper. The data for all publications (○) are averaged over a 10-point range while the data for dead papers (Δ) are averaged over a 5-point range. The straight lines are the best fits for the range shown.

Empirically, unpopular papers are typically cited only soon after publication (if at all) and then disappear. We thus expect that the number of citations to a paper and the average age of these citations are positively correlated. Fig. 6 shows this average citation age versus total number of citations. We also distinguish "dead" and "alive" papers in this plot. While it is not possible to be definitive, we define dead papers as those with less than 50 citations and where the average age of its citations is less than one-third the age of the paper itself. Based on examining the actual data, our definition of dead papers appears generous, as relatively few publications that are considered as dead by this criterion have been cited recently.

As expected, there is a positive correlation between the average citation age $\langle A\rangle$ and the number of times N that a publication has been cited. The dependence is very systematic for fewer than 100 citations, but then fluctuates strongly beyond this point. Over the more systematic portion of the data, power-law fits suggest that $\langle A\rangle \sim N^{\alpha}$, with $\alpha \approx 0.28$ for all publications and $\alpha \approx 0.17$ for dead publications.

As previously alluded to in Sec. III, there are two distinct distributions of citation ages. One is the distribution of citation ages from *citing* publications (Fig. 7). This refers to the age (years in the past) of each citation in the reference list of a paper. The second, and more fundamental, distribution refers to the ages of citations to *cited* publications (Fig. 8). For example, for a paper published in 1980 that is subsequently cited once in 1982, twice in 1988 and three times in 1991, the (cited) citation age distribution has discrete peaks at 2, 8 and 11 years, with respectively weights 1/6, 1/3, and 1/2.

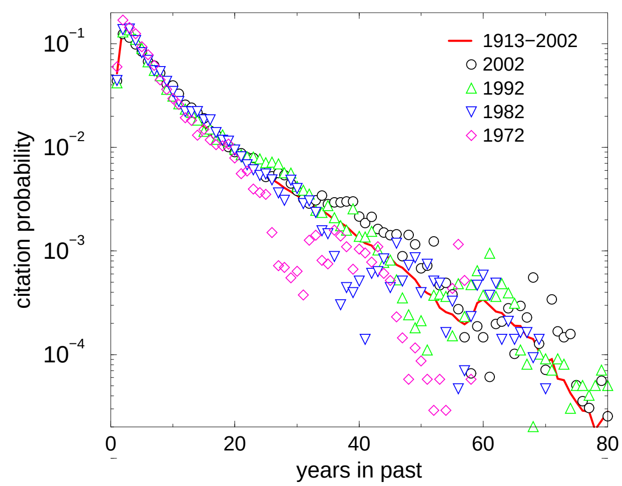

FIG. 7: The distribution of the ages of citations contained in the reference lists of publications that were published in selected years. Also shown is the same distribution for the period 1913-2002.

The distribution of citing ages is shown in Fig. 7 for for papers published in selected years, as well as the distribution integrated over the years 1913-2002. Since the number of old publications is a small fraction of all publications, the integrated distribution does not change perceptibly whether or not earlier publications are included. The annual distributions and the integrated distribution are all quite similar and show the same range of memory for old papers, independent of their publication year. Evidently, citations are driven primarily by memory and not by a preferential attachment mechanism (see Ref. [25] for modeling a decaying memory on the structure of growing networks). Since the probability of citing a paper is proportional to its current number of citations in preferential attachment, this would give preferential citations to older papers – opposite to what is observed. Thus the adage "nobody cites old papers anymore" is figuratively true for PR publications.

In the range of 2 – 15 years, the distribution decays exponentially in time, with a 10-fold decrease in citation probability across a 20-year time span. For longer times, there is a slower exponential memory decay that is masked by the influence of WWII. For example for the 1972 data, there is a pronounced dip between 25 – 30 years. This dip moves 10 years earlier for each 10-year increase in the publication year. Without this dip, the old citation data could well exhibit data collapse. Finally, notice that the integrated distribution has a perceptible WWII-induced dip at 57 years in the past, indicative of the fact that most PR publications have appeared in the last decade.

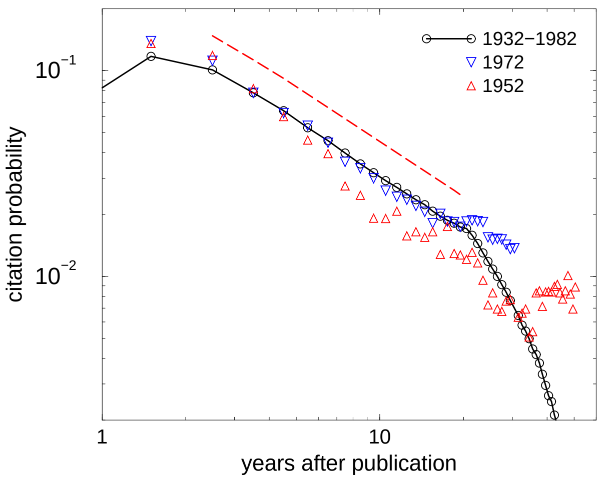

FIG. 8: Distribution of the ages of citations to cited papers in selected years, as well as the integrated data over the period 1932-1982. The dashed line is the best fit to the data in the range 2 – 20 years (displaced for visibility).

We next present the distribution of cited ages. Since Fig. 7 suggests that citations to papers younger than 20 years are incomplete, we consider only older publications. In fact, the cited age distribution for more recent publications has a sharp cutoff when the current year is reached because such papers are still being cited at a significant rate. Fig. 8 shows the age distribution for papers published in two selected years, 1952 and 1972, and as well as the distribution integrated over 1932-1982. Once again, this integrated distribution does not change perceptibly if pre-1932 data are included. For plotting on a double logarithmic scale, we also add 0.5 to all ages, so that a citation occurring in the same year as the original paper is assigned an age of 0.5. Over the limited range of 2 – 20 years, the integrated data is consistent with a power law decay with an associated exponent of -0.94 (dashed line in the figure). Thus even though authors tend to have an exponentially-decaying memory in the publications that they cite, the cited citation age distribution has a much slower power law decay.

VII. CITATIONS BURSTS

Perhaps the most intriguing feature that comes to light by looking at the time history of citations is the existence of occasional strongly-correlated bursts of activity. We present the most prominent examples of such bursts for highly-cited publications, including the generic phenomena of revival of classic works, "hot" publications, and major discoveries.

A. Revival of Old Classics

Sometimes a publication will remain long-unrecognized and then suddenly become in vogue. We define this category of publication as all non-review PR publications (excluding RMP) with more than 300 citations and for which the ratio of average citation age to age of the paper is greater than 0.75. That is, we examined only well-cited papers in which the bulk of their citations occur closer to the present rather than to the original publication date. Remarkably, only 8 papers fit these two criteria. They are:

TABLE III: The 8 PR papers with $>$ 300 citations and with citation age/paper age $>$ 0.75.

Impact Rank	Publication				# cites	Title	Author(s)
4	PR	40	749	1932	568	On the Quantum Correction for Thermodynamic Equilibrium	E. Wigner
7	PR	47	777	1935	532	Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?	A. Einstein, B. Podolsky, & N. Rosen
23	PR	56	340	1939	350	Forces in Molecules	R. P. Feynman
6	PR	82	403	1951	678	Interaction between d-Shells in Transition Metals. II. Ferromagnetic Compounds of Manganese with Perovskite Structure	C. Zener
30	PR	100	545	1955	374	Neutron Diffraction Study of the Magnetic Properties of the Series of Perovskite-Type Compounds $[(1-x)$La,xCa$]$MnO$_3$	E. O. Wollan & W. C. Koehler
37	PR	100	564	1955	302	Theory of the Role of Covalence in the Perovskite-Type Manganites [La, M(II)]MnO$_3$	J. B. Goodenough

TABLE III: The 8 PR papers with > 300 citations and with citation age/paper age > 0.75.

19	PR	100	675	1955	483	Considerations on Double Exchange	P. W. Anderson & H. Hasegawa
21	PR	118	141	1960	519	Effects of Double Exchange in Magnetic Crystals	P.-G. de Gennes

The number of citations in this table have been updated through the end of 2003 (compare with their citations in Table I). The clustering of citation histories of the last 5 of these 8 publications is particularly striking (Fig. 9). These interrelated papers were written between 1951 and 1960, with three in the same issue of Physical Review! They were all concerned with the "double exchange" mechanism in manganites with a Perovskite structure. This interaction is responsible for the phenomenon of colossal magnetoresistance, a topic that became extremely popular through the 90's due to the confluence of new synthesis and measurement techniques in thin-film transition-metal oxides, the sheer magnitude of the effect, and the clever coining of the term "colossal" to describe the phenomenon [27]. The simultaneous extraordinary burst of citations to these articles in a short period close to the year 2000, more than 40 years after their original publication, is unique in the entire history of PR journals.

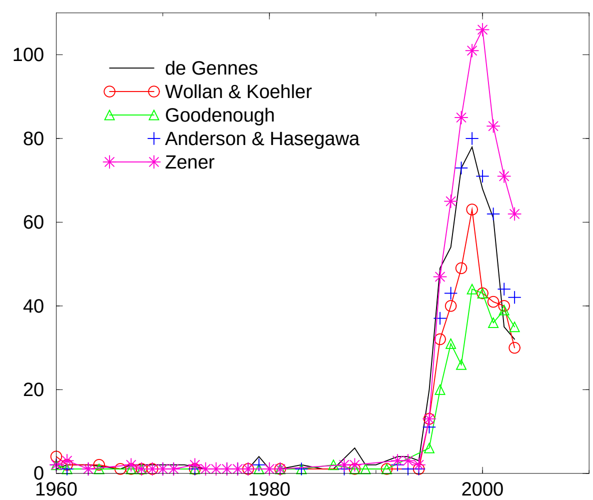

FIG. 9: Citation history of the five publications of relevance to colossal magnetoresistance.

Of the remaining three, the publications by Wigner and by Einstein et al. owe their renewed popularity to the upsurge of interest on quantum information phenomena. Finally, Feynman's work presented a new (at the time) method for calculating forces in molecular systems, a technique that has had wide applicability in understanding interactions between elemental excitations in many fields of physics. This paper is particularly noteworthy because it is cited by papers from all PR journals: PR, PRA, PRB, PRC, PRD, PRE, PRL, and RMP!

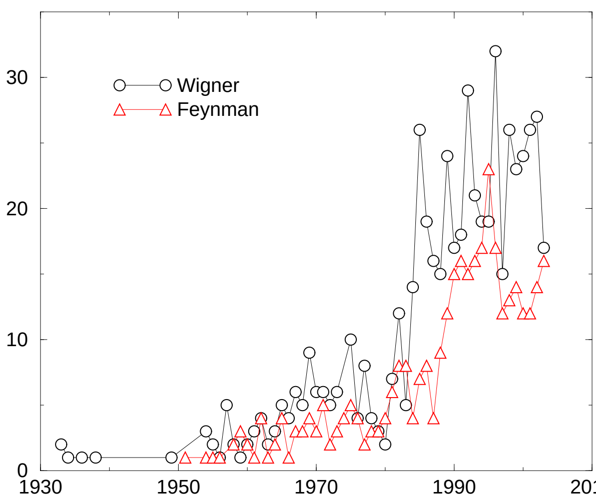

FIG. 10: Citation history of the 1932 paper by Wigner (∘) and the 1939 paper by Feynman (Δ).

By relaxing the conditions on the number of publications and/or the ratio of average citation age to publication age, several more confluences of citation activity can be identified, although none with the intensity of that for colossal magnetoresistance. By extending our consideration to non-review articles with 200 or more citations and with the ratio of average citation age to publication age greater than 2/3, there are a total of 44 publications. This number includes the aforementioned 8 articles that also satisfy the more stringent condition of > 300 citations and also the ratio of average citation age to the age of the publication > 0.75.

Of the 44 articles in this group, we find three generic citation histories. The first is the situation already found in the case of colossal magnetoresistance – rediscovery of an old classic paper, but then the time in the spotlight for such a paper passes. The second is a phenomenon that may be characterized as publications of "enduring interest". These are papers that continue to be cited at a relatively steady or slowly increasing rate over a long time period. The third are "hot" papers, in which the citation rate is increasing rapidly with time.

From these 44 publications, we found that 17 of them fit the citation history of revival of an old classic. They are listed chronologically below:

TABLE IV: The 17 papers with > 200 citations, citation age/paper age > 0.66, and where the current citation rate is decreasing.

Publication				# cites	Av. Age	Impact	Title	Author(s)
PR	46	1002	1934	557	51.49	28680	On the Interaction of Electrons...	E. Wigner
PR	73	360	1948	230	40.75	9372.5	The Influence of Retardation on...	H. B. G. Casimir & D. Polder
PR	81	988	1951	201	36.64	7364.6	A Theory of Cooperative Phenomena	R. Kikuchi
PR	82	403	1951	678	46.35	29803	Interaction between *d*-Shells in...	C. Zener
PR	90	817	1953	212	36.37	7710.4	The Threshold Law for Single...	G. H. Wannier
PR	100	545	1955	374	41.90	14665	Neutron Diffraction Study of...	E. O. Wollan & W. C. Koehler
PR	100	564	1955	302	42.02	11556	Theory of the Role...	J. B. Goodenough
PR	100	675	1955	483	43.22	19924	Considerations on Double Exchange	P. W. Anderson & H. Hasegawa
PR	118	141	1960	519	37.10	18550	Effects of Double Exchange...	P.-G. de Gennes
PRL	8	250	1962	334	28.42	9492.3	Magnetization of Hard Superconductors	C. P. Bean
PRL	10	159	1963	273	28.56	7796.8	Effect of Correlation on the Ferro-...	M. C. Gutzwiller
PRL	10	486	1963	319	28.47	9081.9	Tunneling Between Superconductors	V. Ambegaokar & A. Baratoff
PRL	20	1445	1968	552	23.91	13198	Absence of Mott Transition in...	E. H. Lieb & F. Y. Wu
PRL	23	880	1969	200	27.30	5460.0	Proposed Experiment to Test Local Hidden-Variable Theories	J. F. Clauser, M. A. Horne, A. Shimony, & R. A. Holt
PRD	7	2333	1973	251	22.39	5619.9	Black Holes and Entropy	J. D. Bekenstein
PRD	17	2369	1978	583	17.25	10057	Neutrino Oscillations in Matter	L. Wolfenstein
PRB	37	785	1988	253	11.34	2869.0	Development of Colle-Salvetti...	C. Lee, W. Yang, & R. G. Parr

The reasons why these publications have faded from citation memory generally reflects readily-identifiable changes in current research directions. We comment on this trend for the most highly cited publications in this subset. Wigner's paper is often cited in studies of correlated two-dimensional electron gases, quantum dots, Wigner crystals, and related systems. These were topics that were especially in vogue in the early 90's, a period that coincided with the the peak in citations to Wigner's paper. The Lieb & Wu paper also had a significant citation peak in the early 90's, where many of its citing papers were concerned with a fashionable topic of the time – Hubbard models, t-J models, and their offshoots. The peak in citations to Wolfenstein's papers on neutrino oscillations occurred in 2000, around the same time as the experimental announcement of these oscillations.

We next present publications of the enduring interest. The following 12 publications fit the citation history appropriate for this category:

TABLE V: The 12 papers with > 200 citations, citation age/paper age > 0.66, and where the current citation rate is steady or slowly increasing.

Publication				# cites	Av. Age	Impact	Title	Author(s)
PR	65	117	1944	568	40.13	22794	Crystal Statistics. I...	L. Onsager
PR	69	681	1946	221	43.00	9503.0	SpontaneousEmission...	E. M. Purcell
PR	82	664	1951	663	36.60	24266	On Gauge Invariance and...	J. Schwinger
PR	100	703	1955	209	33.10	6917.9	Stark Effect in Rapidly Varying...	S. H. Autler and C. H. Townes
PR	115	485	1959	484	32.35	15657	Significance of Electromagnetic...	Y. Aharonov & D. Bohm
PR	123	1242	1961	236	31.97	7544.9	Cyclotron Resonance and...	W. Kohn
PR	124	287	1961	263	29.20	7679.6	Conservation Laws and...	G. Baym & L. P. Kadanoff
PR	127	1391	1962	230	28.47	6548.1	Self-Consistent Approximations...	G. Baym
PR	139	A796	1965	402	26.14	10508	New Method for Calculating...	L. Hedin
PR	138	B979	1965	210	26.90	5649.0	Solution of the Schrödinger...	J. H. Shirley
PRB	14	1165	1976	204	18.61	3796.4	Quantum Critical Phenomena	J. A. Hertz
PRD	22	1882	1980	252	16.02	4037.0	Gauge-invariant Cosmological...	J. M. Bardeen

One classic example in this publication category is Onsager's exact solution of the two-dimensional Ising model. The continued citations to Onsager's paper reflects the central role that the Ising model continues to play for understanding a wide variety of cooperative phenomena. Another important example is Schwinger's 1951 paper that is both a fundamental contribution to the development of quantum electrodynamics and is also a calculational *tour de force*. Finally, the paper by Aharonov & Bohm has had long-term exposure both as a textbook example of interference effects that are driven by quantum mechanics, and as part of the current upsurge of interest in quantum information phenomena.

B. Hot Publications

The remaining 15 out of the 44 papers could be characterized as "hot". These are publications where the citation rate is still increasing sharply and the average age of the citations is close to the age of the paper. It is amazing that the most-cited 1965 paper by Kohn & Sham and the second most-cited 1964 paper by Hohenberg & Kohn could still be characterized as hot. Another striking example is Anderson's 1958 publication on localization in disordered systems, where the citation rate has had a similar growth as the two previously-mentioned articles. Notice also that the first 7 of these hot publications are on the top-100 citation impact list (Table I).

Ten of these 15 articles are in condensed-matter physics, while 4 publications are concerned with quantum information phenomena. At the rate that some of the more recent publications on the list below are being cited, many should soon join the initial top-100 citation impact list.

This list of hot publications is listed chronologically below:

TABLE VI: The 15 hot papers those with > 200 citations, citation age/paper age > 0.66, and where the current citation rate is increasing rapidly.

Publication				# cites	Av. Age	Impact	Title	Author(s)
PR	40	749	1932	561	55.76	31281	On the Quantum Correction...	E. Wigner
PR	47	777	1935	492	59.64	29343	Can Quantum-Mechanical Description of Physical...	A. Einstein, B. Podolsky, & N. Rosen
PR	56	340	1939	342	49.29	16857	Forces in Molecules	R. P. Feynman
PR	109	1492	1958	871	32.00	27872	Absence of Diffusion in...	P. W. Anderson
PR	136	B864	1964	2460	28.70	70604	Inhomogeneous Electron Gas	P. Hohenberg & W. Kohn
PR	140	A1133	1965	3227	26.64	85972	Self-Consistent Equations...	W. Kohn & L. J. Sham
PRB	13	5188	1976	1023	20.75	21227	Special Points for Brillouin-...	H. J. Monkhorst & J. D. Pack
PRB	25	4515	1982	336	15.28	5134.1	Transition from Metallic to Tunneling Regimes in...	G. E. Blonder, M. Tinkham, & T. M. Klapwijk
PRL	48	1425	1982	829	15.05	12477	Efficacious Form for...	L. Kleinman & D. M. Bylander
PRL	58	2486	1987	302	11.27	3403.5	Strong Localization of Photons...	S. John
PRB	41	7892	1990	691	9.68	6689.0	Soft Self-Consistent Pseudo-...	D. Vanderbilt
PRL	67	661	1991	280	8.95	2506.0	Quantum Cryptography...	A. K. Ekert
PRB	45	13244	1992	394	8.08	3183.5	Accurate and Simple Analytic...	J. P. Perdew & Y. Wang
PRL	70	1895	1993	495	7.36	3643.2	Teleporting an Unknown...	C. H. Bennett et al.
PRB	47	558	1993	215	7.55	1623.3	Ab Initio Molecular Dynamics...	G. Kresse & J. Hafner

In Fig. 11, we plot the citation history of four of the more recent of these papers. The current citation rate for the hottest of these hot articles is unprecedented over the history of Physical Review.

C. Discoveries and Trend Setting

Major discoveries are often characterized by a sharp spike in citations when the discovery becomes recognized. We are able to readily detect the subset of such publications in which a citation spike occurs close to the time of publication. For this identification, we considered all non-review articles (excluding both RMP and compilations by the Particle Data Group) with more than 300 citations, in which the ratio of average citation age to age of the publication is less than 0.4. There are a total of 39 such publications. Before 1975 most of these publications are in elementary-particle physics (22/25), while after 1984 all 14 such publications are in condensed-matter physics. Part of the reason for this shift is that major CERN-based discoveries in elementary-particle physics were not published in PR journals. There has also been a recent exodus of publications away from PR journals in favor of web-based publications. These factors may contribute as much as generational shifts in research to the

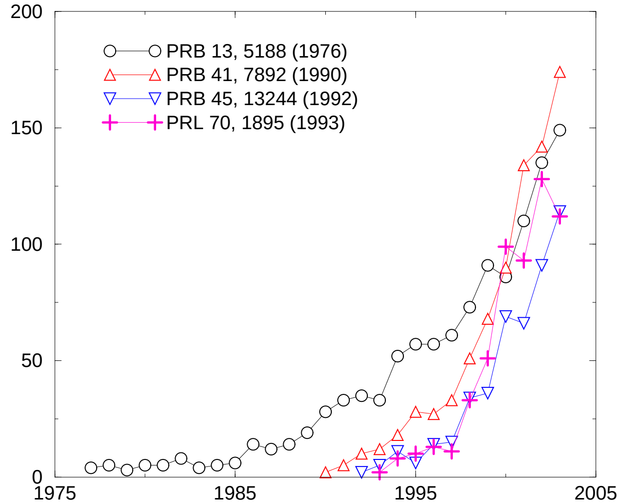

FIG. 11: Citation history of several recent and highly-cited publications in which number of citations are rapidly increasing year by year.

recent lack of elementary-particle physics articles among discovery publications.

With this caveat, the list of discovery publications, according to the criteria of > 300 citations and (average citation age)/(publication age) < 0.4, are listed chronologically below:

TABLE VII: The 39 discovery and/or trend-setting papers with > 200 citations and citation/paper age ratio < 0.4.

	Publication				# cites	Av. Age	Impact	Title	Author(s)
1	PR	106	364	1957	305	18.77	5724.9	Correlation Energy of an Electron Gas at High Density	M. Gell-Mann & K. A. Brueckner
2	PR	109	193	1958	462	10.15	4689.3	Theory of the Fermi Interaction	R. P. Feynman & M. Gell-Mann
3	PR	125	1067	1962	587	7.02	4120.7	Symmetries of Baryons & Mesons	M. Gell-Mann
4	PR	131	745	1963	465	13.20	6138.0	Optical-Model Analysis of...	F. G. Perey
5	PRL	13	138	1964	383	15.74	6028.4	Evidence for the 2π Decay of the $K_2{}^0$ Meson	J. H. Christenson, J. W. Cronin, V. L. Fitch, & R. Turlay
6	PR	141	789	1966	402	12.91	5189.8	Band Structures and Pseudo-...	M. L. Cohen & T. K. Bergstresser
7	PR	148	1467	1966	402	11.49	4619.0	Applications of the Chiral...	J. D. Bjorken
8	PRL	17	616	1966	459	12.48	5728.3	Pion Scattering Lengths	S. Weinberg
9	PRL	18	507	1967	374	9.25	3459.5	Precise Relations Between...	S. Weinberg
10	PR	175	2195	1968	450	10.15	4567.5	Behavior of Current Divergences Under $SU_3 \times SU_3$	M. Gell-Mann, R. J. Oakes, & B. Renner
11	PR	175	747	1968	312	13.59	4240.1	Single-Site Approximations in the Electronic Theory of...	B. Velicky, S. Kirkpatrick, & H. Ehrenreich
12	PR	179	1499	1969	393	10.35	4067.6	Non-Lagrangian Models of...	K. G. Wilson
13	PR	179	1547	1969	305	5.84	1781.2	Asymptotic Sum Rules at...	J. D. Bjorken
14	PR	182	1190	1969	563	13.75	7741.3	Nucleon-Nucleus Optical-Model Parameters, $A > 40$, $E < 50$ MeV	F. D. Becchetti, Jr. & G. W. Greenlees
15	PRL	23	1415	1969	363	7.31	2653.5	Very High-Energy Collisions...	R. P. Feynman
16	PRD	2	1285	1970	738	11.21	8273.0	Weak Interactions with Lepton-Hadron Symmetry	S. L. Glashow, J. Iliopoulos, & L. Maiani
17	PRL	30	1343	1973	423	8.73	3692.8	Ultraviolet Behavior of...	D. J. Gross & F. Wilczek
18	PRL	30	1346	1973	462	8.69	4014.8	Reliable Perturbative Results...	H. D. Politzer
19	PRD	10	2445	1974	577	11.90	6866.3	Confinement of Quarks	K. G. Wilson
20	PRD	9	3471	1974	495	10.94	5415.3	New Extended Model of Hadrons	A. Chodos et al.
21	PRL	32	438	1974	545	11.14	6071.3	Unity of All Elementary...	H. Georgi & S. L. Glashow
22	PRL	33	1404	1974	345	2.92	1007.4	Experimental Observation of a...	J. J. Aubert et al.
23	PRL	33	1406	1974	313	2.74	857.6	Discovery of Narrow...	C. Bacci et al.
24	PRD	12	147	1975	501	10.66	5340.7	Hadron Masses in a Gauge Theory	A. De Rújula, H. Georgi, & S. L. Glashow

TABLE VII: continued from previous page

	Publication				# cites	Av. Age	Impact	Title	Author(s)
25	PRD	12	2060	1975	422	10.28	4338.2	Masses and Other Parameters of the Light Hadrons	T. DeGrand, R. L. Jaffe, K. Johnson, & J. Kiskis
26	PRL	52	1583	1984	302	7.85	2370.7	Statistics of Quasiparticles and...	B. I. Halperin
27	PRL	53	1951	1984	559	7.89	4410.5	Metallic Phase with Long-Range Orientational Order and...	D. Shechtman, I. Blech, D. Gratias, & J. W. Cahn
28	PRA	33	1141	1986	501	6.44	3226.4	Fractal Measures and Their:...	T. C. Halsey et al.
29	PRB	35	1039	1987	307	6.68	2050.8	Universal Conductance Fluctuations in Metals:...	P. A. Lee, A. D. Stone, & H. Fukuyama
30	PRL	58	1028	1987	307	2.66	816.62	Electronic Band Properties...	L. F. Mattheiss
31	PRL	58	2794	1987	525	4.77	2504.3	Theory of high-T_c...	V. J. Emery
32	PRL	58	2802	1987	329	4.02	1322.6	Antiferromagnetism in...	D. Vaknin et al.
33	PRL	58	908	1987	625	1.94	1212.5	Superconductivity at 93K in...	M. K. Wu et al.
34	PRL	60	1057	1988	319	5.42	1729.0	Low-Temperature Behavior of Two-Dimensional...	S. Chakravarty, B. I. Halperin, & D. R. Nelson
35	PRL	60	2202	1988	362	4.81	1741.2	Giant Flux Creep and...	Y. Yeshurun & A. P. Malozemoff
36	PRL	62	1415	1989	447	5.86	2619.4	Vortex-Glass...	M. P. A. Fisher
37	PRL	63	1996	1989	454	5.67	2574.2	Phenomenology of the Normal...	C. M. Varma et al.
38	PRB	43	130	1991	677	5.17	3500.1	Thermal Fluctuations, Quenched Disorder,...	D. S. Fisher, M. P. A. Fisher, & D. A. Huse
39	PRL	70	3999	1993	319	3.88	1237.7	Precision Measurements of...	W. N. Hardy et al.

From the late 50's to the mid-70's, the trend-setting publications clearly reflected the major developments in elementary-particle physics. These included the $V-A$ theory of beta decay (#2 on the list), $SU(3)$ symmetry (#3), CP violation (#5), current algebra methods to determine mass spectra of elementary particles (#8 & 9 on the list), the role of spontaneous symmetry breaking (#10), the development of QCD (#13 & 24), the parton model (#15), the prediction of charm (#16), quark confinement and asymptotic freedom (#17–19), the "MIT bag" model of hadrons (#20 & 25), grand unified theory (#21), and the discovery of the J/ψ particle (#22 & 23).

Another striking feature is that of the 14 condensed-matter physics publications after 1983, 8 of them are devoted to high-temperature superconductivity while another publication investigated type-II superconductors. All but one of the high-T_c articles appeared in the period 1987–1989; evidently this was the golden age of high-temperature superconductivity. Not surprisingly, this subfield represents the strongest coincidence of research activity among these discovery/trend-setting articles.

The citation histories of these discovery publications are again diverse. For example, the average lifetime of citations to the 1974 publications that announced the discovery of the J/ψ particle (#22 & 23 on the above list) is less than 3 years (Fig. 5)! Once the discovery was made and the field progressed, there was evidently little motivation for citing the original papers. The field of high-temperature superconductivity also has given rise to rapid obsolescence, with two publications (#30 & 33 on the above list) having an average citation lifetime of less than 2.7 years and no more than 4 citations annually to these papers after 1996. On the other hand, the oldest publications in this compilation are "Correlation Energy of an Electron Gas at High Density" Phys. Rev. **106**, 364 (1957) by M. Gell-Mann and K. A. Brueckner (305 citations, average citation age 18.77), and "Theory of the Fermi Interaction" Phys. Rev. **109**, 193 (1958) by R. P. Feynman and M. Gell-Mann (462 citations, average citation age 10.15). The disappearance of these papers from current PR citations possibly stems from the fact that the results of these publications are now included in many textbooks.

VIII. DISCUSSION

The availability of a large continuous body of citation data from a major physics journal, Physical Review (PR), provides a unique window with which to observe how subfields evolve and how individual publications can influence subsequent research. It is important, however, to be aware of the limitations of the citation data from PR journals only. For a variety of reasons, many important physics articles have not been published in PR journals; thus much important citation data is simply missing from our study.

In addition, our data does not include citations to PR articles from articles that were not published in PR journals. Their omission is a significant effect. To get a feeling for its magnitude, we provide below the list of 23 elementary-particle physics PR articles that had been cited more than 1500 times at the end of 2003 from all sources, as tabulated by the SPIRES database [26]. This compilation extends to 52^{nd} place among papers in the all-time citation rank. Also included is the number of internal citations (citations from other PR publications), also by the end of 2003. The ratio of internal to total citations falls in range of 0.19 – 0.36 for all the listed articles.

TABLE VIII: The 23 PR publications in elementary-particle physics with > 1500 total citations from all sources, according to the SPIRES database. The number of PR cites through the end of 2003 are also shown.

Publication				PR cites	total cites	Title	Author(s)
PRL	19	1264	1967	1311	5424	A Model of Leptons	S. Weinberg
PRD	2	1285	1970	742	3077	Weak Interactions with Lepton-Hadron...	S. L. Glashow, J. Iliopoulos, & L. Maiani
PRD	10	2445	1974	589	2620	Confinement of Quarks	K. G. Wilson
PRL	32	438	1974	554	2587	Unity of All Elementary Particle Forces	H. Georgi & S. L. Glashow
PR	122	345	1961	698	2403	Dynamical Model of Elementary...	I. Y. Nambu & G. Jona-Lasinio
PRD	14	3432	1976	463	2401	Computation of the Quantum Effects...	G. 't Hooft
PRD	10	275	1974	621	2326	Lepton Number as the Fourth Color	J. C. Pati & A. Salam
PRD	23	347	1981	695	2231	Inflationary Universe:...	A. H. Guth
PRD	17	2369	1978	593	2217	Neutrino Oscillations in Matter	L. Wolfenstein
PRL	37	8	1976	468	2110	Symmetry Breaking Through Bell-Jackiw...	G. 't Hooft
PRD	7	1888	1973	603	2071	Radiative Corrections as the Origin of...	S. Coleman & E. Weinberg
PRL	30	1346	1973	465	1960	Reliable Perturbative Results for Strong...	H. D. Politzer
PRL	30	1343	1973	426	1953	Ultraviolet Behavior of Non-Abelian...	D. J. Gross & F. Wilczek
PR	82	664	1951	678	1951	On Gauge Invariance and Vacuum...	J. Schwinger
PRL	81	1562	1998	479	1948	Evidence for Oscillation of Atmospheric Neutrinos...	Y. Fukuda et al. (Super-Kamiokande Collaboration)
PR	177	2426	1969	521	1911	Axial-Vector Vertex in Spinor...	S. L. Adler
PRL	83	3370	1999	468	1886	A Large Mass Hierarchy From a Small...	L. Randall & R. Sundrum
PRL	83	4690	1999	473	1833	An Alternative to Compactification	L. Randall & R. Sundrum
RMP	56	579	1984	411	1695	Super Collider Physics	E. Eichten et al.
PRD	22	2157	1980	503	1661	Exclusive Processes in Perturbative QCD	G. P. Lepage & S. J. Brodsky
PRL	10	531	1963	590	1586	Unitary Symmetry and Leptonic Decays	N. Cabibbo
PRD	12	147	1975	510	1554	Hadron Masses in a Gauge Theory	A. De Rújula, H. Georgi, & S. L. Glashow
PRD	9	3320	1974	531	1542	Symmetry Behavior at Finite Temperature	L. Dolan & R. Jackiw

The significant difference between the number of PR citations and all citations provides a sense of the incompleteness of the PR data. It would therefore be worthwhile to extend this citation study to include a broader range of physics journals to see if such an extension would lead to qualitatively different citation patterns.

Turning to results, one of our basic observations is the striking confluences of citation activity during the history of Physical Review. Several of the most prominent of these confluences are quite recent but are based on work of more than a half century ago. Another noteworthy feature is the large role that a relatively small number of individual physicists have played in the top-100 citation impact publications in PR journals, with two individuals each co-authoring five of these articles.

There is also a small number (15) of "hot" PR publications that have been cited at a remarkable rate in the past few years. Much of this activity – 5 articles – revolves around density functional theory, pseudopotential methods, and the development of accurate techniques for band structure calculations. The origin of a significant fraction of this work is, in turn, the pioneering Kohn-Sham paper of 1965. The only other topical coincidence in this subset of publication is of quantum information theory; this is the subject of 4 publications. Part of the reason for the large citation rate to these hot papers could well be the larger number of researchers compared to several decades ago, as well as the rapid availability of preprints through electronic archives. Nevertheless, the very rapid and recent growth in citations of these publications seem to portend scientific advances.

Once again, however, being limited to citations within PR publications gives an incomplete picture. While hot PR publications in condensed-matter physics are cited internally approximately 200 times per year, the citation rate from all sources is likely much larger. In fact, there are 3 recent and hot articles in elementary-particle physics with a citation rate of at least 400 per year according to the SPIRES database. The are: "The Large-N Limit of Superconformal Field Theories and Supergravity", J. M. Maldacena, Adv. Theor. Math. Phys. **2**, 231 (1998), with 2898 citations at the end of 2003, "Anti-De

Sitter Space and Holography", E. Witten, Adv. Theor. Math. Phys. **2**, 253 (1998), with 2062 citations, and "The Hierarchy Problem and New Dimensions at a Millimeter", N. Arkani-Hamed, S. Dimopoulos & G. R. Dvali, Phys. Lett. **B429**, 263 (1998), with 2009 citations. Given the larger size of condensed-matter physics, we anticipate that the total citation rates to the hot publications in this field are much larger than 400 annually.

As a final note, it is important to emphasize that citations are an imperfect measure of the quality of scientific publications and the use of citation activity in guiding policy decisions has to be made with great caution.

IX. ACKNOWLEDGMENTS

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