RECAPTURING PHYSICS IN THE 1920s THROUGH CITATION ANALYSIS*)

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Data on highly cited papers from a recently compiled citation index for physics in the 1920s are explored in relation to the revolutionary developments that are widely regarded as constituting a golden age in physics. It is found that most of the "classic" papers which we recognize today as having brought about the revolution in quantum and wave mechanics during the 1920s are associated with spiked patterns of citation, some papers being cited more the first year after they were published than any later year. In contrast, papers with less dramatic ascents, which may have received comparable numbers of citations over their lifetime, were associated with concepts or procedures which are now forgotten. It is hypothesized that our recollections and perceptions of the past favor the sudden and dramatic developments over the slow and steady ones.

The 1920s are widely regarded as the "golden age" of physics, when a small band of creative individuals reshaped the fundamental theoretical structure of their discipline. Around this remarkably creative period has evolved what might be called an "official history". The discipline of physics has taken an active interest in its history, and physicists have an awareness of aspects of their past acquired through the recollections of the older generation, and textbook histories which attempt to show the cultural and conceptual antecedents of currently useful theory.

A citation analysis of the physics literature of the 1920s may be expected to uncover two distinct categories of earlier physics: 1) remembered because of its relevance to the present, and 2) forgotten because of its irrelevance. Citation analyses are usually concerned with events during the recent past simply because the Science Citation Index^{R} only goes back to 1955 [1]. Rarely do citation analysts have the opportunity to ply their trade on an "old" literature whose history has been seriously studied, and whose achievements are so heroic. An enthusiastic proponent of citation analysis might claim: "Now we will find out what really happened." My goals are somewhat more modest. I admit the possibility that the myth may contain a kernel of truth: in citation terms, this means that what are regarded today as important advances in physics were recognized as important then and this is reflected in their high citation rate during the period. I also expect to uncover, a large lode of "forgotten" history, which is as important for understanding the physics of the 1920s, as is the "remembered" component.

The base which I am using was compiled from a set of 16 "core" physics journals (see table 1) all active during the 1920s [2]. When data entry was completed, this citation index consisted of about 21 000 source items and about 165 000 references spanning the decade. There are, of course, as many ways to approach this database as there are data elements in it. We might enquire at the level of the individual physicist, the institutions in which they worked, the journals they published in and their countries of origin. I have chosen, for the purpose of this first reconnoitering, to restrict my attention to the unit of the cited document, particularly focusing upon those that are highly cited. One might argue that this is the most fundamental level of analysis possible using a citation index since the document is the primitive element from which the larger aggregates of individual and institution are formed. I feel that the only justification

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Table 1

Source journal coverage of Physics Citation Index

publishing country	journal title	1920—1929 source items	1920—1929 references
Germany	Zeitschrift für Physik	3 555	40 698
	Annalen der Physik	1 265	19 621
	Physikalische Zeitschrift	2 622	15 308
England	Monthly Notices of the Royal Astronomical Society	1 135	7 979
	Philosophical Magazine	2 573	17 119
	Proceedings of the Royal Society of London, Section A	1 454	15 407
	Proceedings of the Physical Society	594	3 625
	Philosophical Transactions of the Royal Society of London, Section A	95	2 177
United States	Physical Review	4 616	18 329
	Astrophysical Journal	667	8 793
France	Journal de Physique	446	3 808
	Annales de Physique	158	4 384
Italy	Il Nuovo Cimento	483	2 144
Denmark	Matematisk-Fysiske Meddelelser Kongelige Danske Videnskabernes Selskab	102	1 732
Netherlands	Physica	861	3 011
Japan	Proc. Physico-Mathem. Soc. Japan (Nippon Sugaku-buturigakkwai Kiji)	523	947
total		21 149	165 082

required is to say that no other unit of analysis permits one to study the impact of ideas in terms of the citations to the documents that embody, or were thought to embody, those ideas.

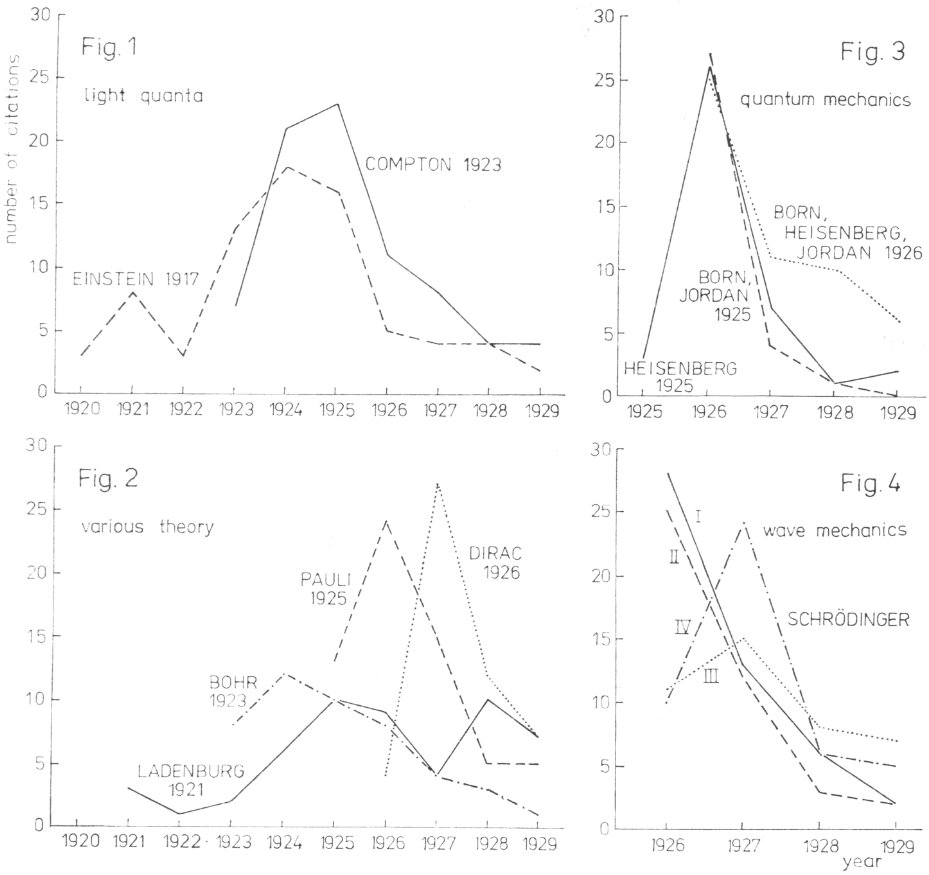
It should be kept in mind that a proper analysis of citations (to documents at least), includes an examination of citation contexts as well as a counting of citations. Such a content or context analysis can reveal unexpected "readings" of the cited papers made by the citing authors, which differ from our contemporary reading of the same texts. Hence, the significance or "meaning" of any cited work must ultimately rest with the citing authors, and not with our reading of the cited text or a citation count.

These preliminaries aside, I would like to examine the list of 13 most cited papers from 1920 to 1929, and see both the "remembered" and "forgotten" components.*). We see in this abbre-

*) Note: I have used total citations over the decade 1920—29 to rank these papers even though this biases against papers published later in the decade. A more sophisticated analysis might utilize the citations received per year after publication. Despite this bias many papers from late in the decade appear on the list of papers cited 40 or more times, which attests to the rapid expansion of the field as well as the dramatic impact of the new findings. For a complete listing of these papers see: Small H.: A Citation Index for Physics: 1920—1929. Final Report on National Science Foundation Grant SOC 77—14 957 (September, 1980).

viated list hints of more general principles which hold for items lower on the list. First, we note that the two most cited items both had to do with the quantum nature of light: from an experimental verification (the Compton effect) to an earlier (1917) theoretical justification by Einstein. We note on the time series the coincident peaks from 1924 to 1925 for both papers. Two clear items with quantum mechanical significance are Pauli 1925 and Dirac 1926. The Pauli item, though by no means obvious from its title, is in fact the first statement of what came to be known as the Pauli exclusion principle; the Dirac paper, according to Jammer [4] is remembered for introducing what was later named for someone else, the Slater determinants.

Ladenburg's 1921 paper, like most of the papers in this top 13, was written before the discoveries of the quantum and wave mechanics, but may be regarded, with Pauli's 1925 paper, as a theoretical percursor. Van der Waerden [5] points out that Ladenburg introduced in this paper on the classical formula for absorption lines, the concept of "virtial oscillators" which became important later in the decade in finding a way to the new quantum theory. Note the peaking of citations to this item and Pauli's in 1926. The item by Birge and Sponer is a different story. It is essentially an empirical procedure for determining the energy of dissociation of non-polar diatomic molecules from band spectra data. Physicists I have asked about this paper have not admitted familiarity with the "Birge-Sponer" method, nor have I found it mentioned in the available histories. Thus, it may be a forgotten classic.



Figs. 1—4.

Table 2. Most cited documents and other documents referred to in text and figures

Author / *Title*	Journal	*vol.*	year	page	1920—1929 citations	# yrs
COMPTON A. H.	Phys. Rev.	*21*	(1923)	483	78	(7)
A quantum theory of the scattering of X-rays by light elements						
EINSTEIN A.	Phys. Z.	*18*	(1917)	121	76	(10)
Zur Quantentheorie der Strahlung						
PAULI W.	Z. Phys.	*31*	(1925)	765	62	(5)
Über den Zusammenhang des Abschlusses der Elektronengruppen im Atom mit der Komplexstruktur der Spektren						
HUND F.	Z. Phys.	*33*	(1925)	345	61	(5)
Zur Deutung verwickelter Spektren, insbesondere der Elemente Scandium bis Nickel						
DEBYE P.	Phys. Z.	*13*	(1912)	97	60	(10)
Einige Resultate einer kinetischen Theorie der Isolatoren						
DEBYE P., HÜCKEL E.	Phys. Z.	*24*	(1923)	185	58	(7)
Zur Theorie der Elektrolyte						
BIRGE R. T., SPONER H.	Phys. Rev.	*28*	(1926)	259	56	(4)
The heat of dissociation of non-polar molecules						
KRATZER A.	Z. Phys.	*3*	(1920)	289	56	(10)
Die ultraroten Rotationsspektren der Halogenwasserstoffe						
KLEIN O., ROSSELAND S.	Z. Phys.	*4*	(1921)	46	56	(9)
Über Zusammenstöße zwischen Atomen und freien Elektronen						
KRAMERS H. A.	Phil. Mag.	*46*	(1923)	836	53	(7)
On the theory of X-ray absorption and of the continuous X-ray spectrum						
LADENBURG R.	Z. Phys.	*4*	(1921)	451	52	(9)
Die quantentheoretische Deutung der Zahl der Dispersions-elektronen						
BORN M., HEISENBERG W., JORDAN P.	Z. Phys.	*35*	(1926)	557	52	(4)
Zur Quantenmechanik, II.						
DIRAC P. M. A.	P. Roy. Soc. A	*112*	(1926)	661	50	(4)
On the theory of quantum mechanics						
other						
RAMSAUER C.	Ann. Physik	*64*	(1921)	513	49	(9)
Über den Wirkungsquerschnitt der Gasmoleküle gegenüber langsamen Elektronen						
SCHRÖDINGER E.	Ann. Physik	*79*	(1926)	361	49	(4)
Quantisierung als Eigenwertproblem I						
... II	Ann. Physik	*79*	(1926)	489	42	(4)
...III	Ann. Physik	*80*	(1926)	437	41	(4)
...IV	Ann Physik	*81*	(1926)	109	43	(4)
BOHR N.	Z. Phys.	*12*	(1923)	342	47	(7)
Röntgenspektren und periodisches System der Elemente						

Table 2 (Continued)

Author / *Title*	Journal	*vol.*	year	page	1920—1929 citations	# yrs
BOHR N.	Phil. Mag.	*30*	(1915)	581	44	(10)
On the decrease of velocity of swiftly moving electrified particles in passing through matter						
PASCHEN F.	Ann. Physik	*60*	(1919)	405	43	(10)
Das Spektrum des Neon						
HEISENBERG W.	Z. Phys.	*33*	(1925)	879	39	(5)
Über quantentheoretische Umdeutung kinematischer und mechanischer Beziehungen						
SCHRÖDINGER E.	Ann. Physik	*79*	(1926)	734	36	(4)
Über das Verhältnis der Heisenberg-Born-Jordanschen Quantenmechanik zu der meinen						
BORN M., JORDAN P.	Z. Phys.	*34*	(1925)	858	32	(5)
Zur Quantenmechanik I						
BOHR N.	Phil Mag.	*26*	(1913)	1	17	(10)
On the constitution of atoms and molecules, Part I						
... II	Phil. Mag.	*26*	(1913)	476	14	(10)
...III	Phil. Mag.	*26*	(1913)	857	15	(10)

We note in the list of top 13, a mix of theoretical and experimental papers. While it is often difficult to place papers in this neat dichotomy, categorization of the top 45 papers (cited 40 or more times) yields about 60% theory and 32% experimental. Another striking feature not related to the theory/experiment dimension is the persistent pattern of citation for certain papers and the rapid growth and decay pattern for others. In the former category we could place the 1912 Debye paper on the theory of insulators and the 1920 Kratzer papers on the rotation spectra of hydrogen — halogen molecules. The same persistence can be easily discerned for papers lower on the list: Ramsauer's 1921 paper on the cross-section of gas molecules for slow electrons, Paschen's 1919 paper on the spectrum of neon, and Bohr's 1915 paper on the decrease in velocity of charged particles passing through matter. Many of these persistent papers are in effect theories of phenomena frequently encountered in the laboratory, and thus may well have had a continuing importance for the interpretation of data. They were, in short, useful methods, procedures or formulas. Ironically, Bohr's early papers on what was known as stopping power outlasted his classic 1913 trilogy of papers on atomic structure. By the 1920s the latter were infrequently cited.

Another significant class of papers has a distinctly different citation pattern. These are the rapid rise and fall papers, many of which turn out to be the theoretical papers we now regard as the primordial papers in quantum and wave mechanics. Taking first the quantum mechanical approach, the series of papers by Heisenberg, Born and Jordan are usually considered the earliest statements of the new theory. Heisenberg's 1925 paper was the first, followed by a Born and Jordan paper in 1925 and then a Born, Heisenberg and Jordan paper in 1926 (the so-called "Drei-Männer Arbeit").

Two of these three are in the group of 45 papers cited 40 or more times and the Born/Jordan paper is cited 34 times. The initial Heisenberg paper peaks in 1926, the year after its publication and the two follow-up papers were cited more in the year they were published than any later year. All experienced rapid declines in citation rate after the first two years. The same pattern holds for Schrödinger's papers on wave mechanics. His theory was presented in a series of four papers published in Annalen der Physik in 1926, in addition to a paper showing the equivalence of the Heisenberg-Born-Jordan theory to his own. All five of these Schrödinger papers appear on the list of 45 papers cited 40 or more times. Three of the five were cited more during the year of their publication than any later year, and the other two peaked one year after publication, and then declined rapidly.

Rapid rise and decline holds for numerous theoretical papers, as illustrated by table 2. Such rapid reaction to innovation is indeed surprising to find in the 1920s, as is the rapid decline. However we account for this, we can conclude that the mythology of the golden age is not a fabrication. Papers embodying results now seen as laying the foundation of the new theory *were* highly cited at the time of their appearance. The reason for their rapid disappearance from view may be obsolescence and replacement by new formulations, but only more detailed investigation can reveal the mechanism.

We are inclined to hypothesize that the "remembered" classics tend to be those having a spiked pattern of citation, i.e., dramatic receptions, while the "forgotten" classics are those items with less dramatic but more persistent citation patterns. Perhaps the impact of a work is more the results of momentary high visibility in history than the integration of steady but lower visibility. As important as confirmation of the official history, our citation study has brought to light numerous forgotten and obliterated papers which were clearly important during the period, and thus of great significance for recapturing and understanding the physics of the 1920s.

Historical research has only just begun using the Physics Citation Index 1920—1929 [6, 7].

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