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How can revivals of scientific publications be explained using bibliometric methods? A case study discovering booster papers for the 1985 Physics Nobel Prize paper

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Abstract

The unusual citation profile of the 1985 Physics Nobel Prize paper has been analyzed. The number of citing papers per year exhibits a maximum of 123 citations in the mid-1980s and increases to more than 200 citations about two decades later. The publication set of the citing papers was analyzed in terms of co-authorships and research topics. The USA and (more recently) the People's Republic of China appear prominently among the countries of the citing authors. A keyword analysis of the citing papers revealed research dealing with topological insulators as one of the major newly evolving research topics. An analysis of the co-cited papers has been performed via reference publication year spectroscopy (RPYS). The most-frequently co-cited papers (the peak papers of the RPYS spectrogram) were identified and discussed. As a result, we found two primary booster papers and three secondary booster papers that renewed the interest in the 1985 Physics Nobel Prize paper.

Keywords Bibliometrics · 1985 Physics Nobel Prize paper · Booster paper · Quantum Hall effect · RPYS

Introduction

Scientific publications (especially journal articles) usually increase their number of citations per year during the first few years after publication before exhibiting a more or less distinct peak. Afterwards, the number of citations per year overall declines. The position of the citation peak mainly depends on the field. However, there is also a variation between publications in the same field regarding the peak location. Normal publications decay to a very low number of citations that is close to zero after several years. This can be explained by the gradual obsolescence of the publications' contents (Seglen, 1992). Citation classics (Garfield, 1977) decay slower and to a higher annual number of citations. It is, however, very unusual if the annual citation profile has already declined and leveled off to a certain number of citations per year and many years (maybe decades)

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later increased drastically in the number of citations per year, e.g., reaching twice of the number of citations of the peak a few years after publication. Such an annual citation profile indicates a new or renewed interest in the cited publication. As explained below, the 1985 Physics Nobel Prize paper turned out to exhibit such an unusual citation profile.

The 1985 Physics Nobel Prize was awarded to a single person—Klaus von Klitzing—"for the discovery of the quantized Hall effect" (Nobel Prize Outreach AB 2021, 1985) that was presented in a paper published in 1980 (von Klitzing et al., 1980). At that time in 1980, it was unexpected that an electrical resistance on a solid-state device could exclusively depend on fundamental physical constants: The Hall resistance of a two-dimensional charge carrier system shows well defined plateaus as function of charge carrier density or applied magnetic flux density, given by $R_H = h/(\nu e^2)$ where $\nu = i$ is an integer number, e the elementary charge, and h the Planck constant. At high magnetic field the eigenenergy spectrum for the charge carriers gets discrete, energy gaps appear, so-called Landau levels are formed in a homogeneous system. Charge carrier localization due to disorder, stabilizing an insulating bulk within the two-dimensional charge carrier system, plays obviously an important role for the plateau width. In two-dimensional electron systems (2DES) of higher quality, in 1982 Hall resistance plateaus with rational fractional ν were observed, honored by the Nobel Prize in 1998, nowadays denoted as fractional quantum Hall effect. Their existence has been related to electron–electron correlations within the 2DES, leading to the appearance of an energy gap and therefore electrical incompressibility/insulation for certain ratios of electron number and magnetic flux quanta sharing the same area of a homogenous 2DES. With improving sample quality and reaching lower temperature, more and more exotic quantum Hall states have been observed, challenging the theoretical understanding and triggering even ideas for application in quantum computation.

Klaus von Klitzing realized from the beginning the importance of the integer quantum Hall effect for metrology (von Klitzing, 2019). Since 1990, the quantized Hall resistance has been used as resistance standard. The accuracy of the quantized Hall resistance has been confirmed to better than 10^{-8} by comparing quantum Hall devices based on different materials—since 2003 also including single-atom layer thin flakes like graphene (Physics Nobel Prize in 2010). Remarkably, due to the band structure of graphene the electrons behave there as massless Dirac fermions. The integer quantum Hall effect paved the path for the fundamental redefinition of the SI Units in 2019, eliminating the use of artifacts like the unique representation of 1 kg in Paris, France.

Quantum Hall samples have in common an insulating bulk and conductive edges, induced by the applied magnetic field; they represent a special type of topological insulator. Realizing this, since then materials have been classified—based on their band structure properties—in categories of topological insulators with special edge or surface state properties.

The 1985 Physics Nobel Prize paper turned out to be a citation classic. Its annual number of citations increased approximately linearly from 1980—the year of publication—until 1986 to 123 citing papers (see Fig. 1). Afterwards, its annual number of citations decreased approximately linearly until 1990 and leveled off to about 70 citing papers per year. About one and a half decades later, the number of annual citations increased drastically up to 293 citing papers in 2021. This indicates a new or renewed interest in the 1985 Physics Nobel Prize paper. In this study, we aim to answer the following research questions: What is the cause of this renewed interest? What sparked this renewed interest? Can we identify a specific paper (or group of papers) that initiated this late increase in annual number of citations? Which of the topics of the before briefly described timeline of events is related to the

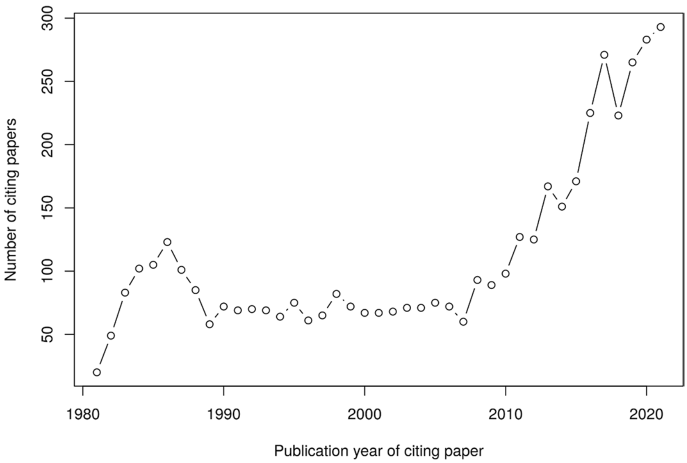

Fig. 1 Annual citation profile of the 1985 Physics Nobel Prize paper. Citing papers from 2022 were excluded from this plot because this year was incomplete at the time of data collection

renewed interest? Papers that initiate such a renewed interest in other papers may be called "booster papers" because they boost the annual citation profile of other papers.

We propose to compare the results from term co-occurrence maps (keywords, author's names, and author's countries) with co-citation analysis results, especially in the time period shortly before the increasing number of annual citations. The annual number of citations started to increase in 2008 as this number has not reached such a level since 1988. Considering citation and indexing delays, we start the search for booster papers a couple of years earlier, i.e., in this case in 2005. We expect that the relevant booster papers were published until 2010 as the citation profile shows an overall continuous growth since 2008 with the exception of a few years. If topics of very frequently co-cited papers can be found in the topic map of the citing papers of the focal paper (here: the 1985 Physics Nobel Prize paper), the very frequently co-cited papers are very likely to have had a booster effect on the focal paper. The more prominent the topics of the co-cited papers, the more likely it is that booster papers are being identified. If additionally, authors and authors' countries of all citing papers of those very frequently co-cited papers can be found in the maps of the citing papers of the focal paper, the likelihood increases that those very frequently co-cited papers had a booster effect on the focal paper.

Methods and dataset

We used data from Web of Science (WoS; Birkle et al., 2020) provided by Clarivate Analytics. We extracted all metadata (with cited references) from all papers citing the 1985 Physics Nobel Prize paper on October 20, 2022, from the web interface of WoS (https://login.webofknowledge.com). Papers citing the 1985 Physics Nobel Prize paper were searched via the cited reference search using all editions (i.e., citation indices) of WoS core collection: Science Citation Index Expanded, Social Sciences Citation Index, Arts & Humanities Citation Index, Conference Proceedings Citation Index—Science, Conference Proceedings Citation Index—Social Science & Humanities, Book Citation Index—Science, Book Citation Index—Social Sciences & Humanities, Emerging Sources Citation Index, Current Chemical Reactions, and Index Chemicus. Although the 1985 Physics Nobel Prize paper is indexed in WoS, many citing papers are not linked to it. Therefore, a cited reference search is necessary for obtaining a complete dataset. We used the following cited reference search data: (1) cited author: 'klitzing* or vonklitzing* or "von klitzing*"', (2) cited work: '(physical review letters) or (phys. rev. lett.)', and (3) cited year: '1980'. We retrieved the metadata of 4770 publications. Figure 1 shows the unusual annual citations profile.

We used VOSviewer (van Eck & Waltman, 2010) to map the co-occurrence of author-keywords, co-authors, and countries of authors of the papers citing the 1985 Physics Nobel Prize paper. The distance between two nodes is determined by the co-occurrence frequency of the terms. The size of the nodes is dependent on the number of papers with a specific keyword, co-author, or author country. Nodes can be colored according to various characteristics (e.g., cluster assignments, average number of citations, or average publication years). We color the nodes according to the average publication years of the publications connected to them.

We included all author keywords that occurred at least five times. The co-authorship map was constructed based on co-authors that appeared at least ten times. The two name variants 'vonklitzing, k' and 'von klitzing, k' were unified to 'von klitzing, k'. We included all countries that occurred at least five times in the author's affiliations. These thresholds were determined to produce meaningful maps. In addition to the static VOSviewer maps, we produced interactive versions via VOSviewer Online (van Eck & Waltman, 2021a, 2021b).

The references cited in the citing papers were analyzed with regard to the frequencies of the reference publication years using CRExplorer (https://crexplorer.net; Thor et al., 2016a, 2016b; Thor et al., 2018a, 2018b). This analysis is called RPYS-CO (Reference Publication Year Spectroscopy based on co-cited papers). In this case, all papers that are co-cited with the marker paper (the 1985 Physics Nobel Prize paper) were analyzed. This analysis takes advantage of the fact that concurrently cited (co-cited) papers are more or less closely related to each other. One can select the citation environment of a specific reference (here: the 1985 Physics Nobel Price paper) in the form of all co-cited references (here: 107,284 distinct co-cited references) and analyze these co-cited references. CRExplorer offers the possibility of automatically clustering and merging variants of the same co-cited reference. We used this possibility with a Levenshtein threshold of 0.75 using volume and page numbers for clustering the co-cited references. This procedure aggregated 404 co-cited references. To sharpen the spectrogram, we removed all co-cited references that occurred less than ten times. This procedure removed 103,481 co-cited references. The remaining set of 3399 co-cited references was analyzed. We extracted for each co-cited reference values such as the reference publication year (RPY), the number of co-cited references (N_CR), and the proportion to which they are responsible for the sum of all N_CR values in the corresponding RPYs (PERC_YR). PERC_YR values depend on the N_CR threshold below which co-cited references are discarded (here, the N_CR threshold of ten was used, see above).

The RPYS-CO method (Haunschild & Marx, 2019, 2020; Marx et al., 2017) is an extension of the standard RPYS method (Marx et al., 2014; Marx, 2021), which enables one to reveal the origins or historical roots of research topics. The RPYS-CO method has been applied to some research topics, e.g., density functional theory (Haunschild & Marx, 2020) and climate change (Marx, et al., 2017) while the standard RPYS methodology has been applied broader so far, e.g., references cited in a journal (Haunschild et al., 2019), health equity (Yao et al., 2019), individual researchers (Bornmann et al., 2018; Bornmann & Haunschild 2023; Leydesdorff et al., 2016). The specific cited reference in RPYS-CO should be a prominent and seminal work, which is used as a kind of marker paper or tracer reference for a specific research topic. We assume that papers, which cite the selected marker paper, are potential candidates for also citing many other references relevant in a subject-specific context. Therefore, these co-cited papers will be suitable candidates for our search for booster papers.

The RPYS spectrogram was plotted using R (R Core Team, 2018) with the R package 'BibPlots' (Haunschild, 2021). In addition to the static RPYS plot in this paper, we produced an interactive RPYS graph using the R package 'dygraphs' (Vanderkam et al., 2018). We analyzed the RPYS spectrogram regarding relevant peaks of the five-year median deviation. Tukey's fences (Tukey, 1977) were used to support the identification of the most important peaks: Important peaks are flagged based on the interquartile range of the median deviations (Bornmann et al., 2018). Special emphasis during the RPYS analysis is put on the time period between 2005 and 2010, because we expect to find booster papers in this time period based on the annual citation profile in Fig. 1.

Results

Figure 2 shows the co-occurrence network of 96 author keywords of the papers citing the 1985 Physics Nobel Prize paper. Before constructing the network, we merged obviously synonymous keywords and deleted too general keywords using a VOSviewer thesaurus file, see Appendix. That step has not required specific knowledge about the topic. The keyword "uncertainty" was disconnected from the network. Thus, we dropped this keyword, too. The nodes are colored by the average publication year.

Not surprisingly, the keywords 'quantum Hall effect' with the satellites 'integer quantum Hall effect', 'fractional quantum Hall effect', and 'two-dimensional electron system' have a rather old average publication year. In contrast, the strong appearance of the keyword 'topological insulator' in recent years is striking. It links other—young—keywords to the keyword 'quantum Hall effect', i.e., 'topological materials', 'topological phase', 'topological phase transition', 'topological photonics', 'topological semimetal', 'topology', 'band inversion', 'spin-orbital coupling', 'spintronics', 'Weyl semimetal', 'bulk-edge correspondence', 'Chern insulator', 'Chern number', 'quantum anomalous Hall effect', 'photonic crystal', to mention some of those. It appears as a very recent, strong extension of the original field. Less pronounced but also with weight in recent years—although on average more in the past—are those keywords which are linked to 'graphene' (with the new keyword 'Dirac particle'), and 'metrology' ('international system of units', 'Kibble balance', 'von Klitzing constant' etc.). The graph reflects obviously the development of the quantum Hall effect as outlined in the introduction.

Moreover, the graph shows quantitatively the scientific interest in terms of publications in the respective field, represented by the keyword's node size. The keyword 'edge state' has a relatively strong weight and is located between both central keyword nodes 'quantum Hall effect' and 'topological insulator', with connections to both sides. The keyword was obviously present already before the new field 'topological insulator' became important. By that, the graph tells us, there seems to be a deeper connection, which is indeed the case:

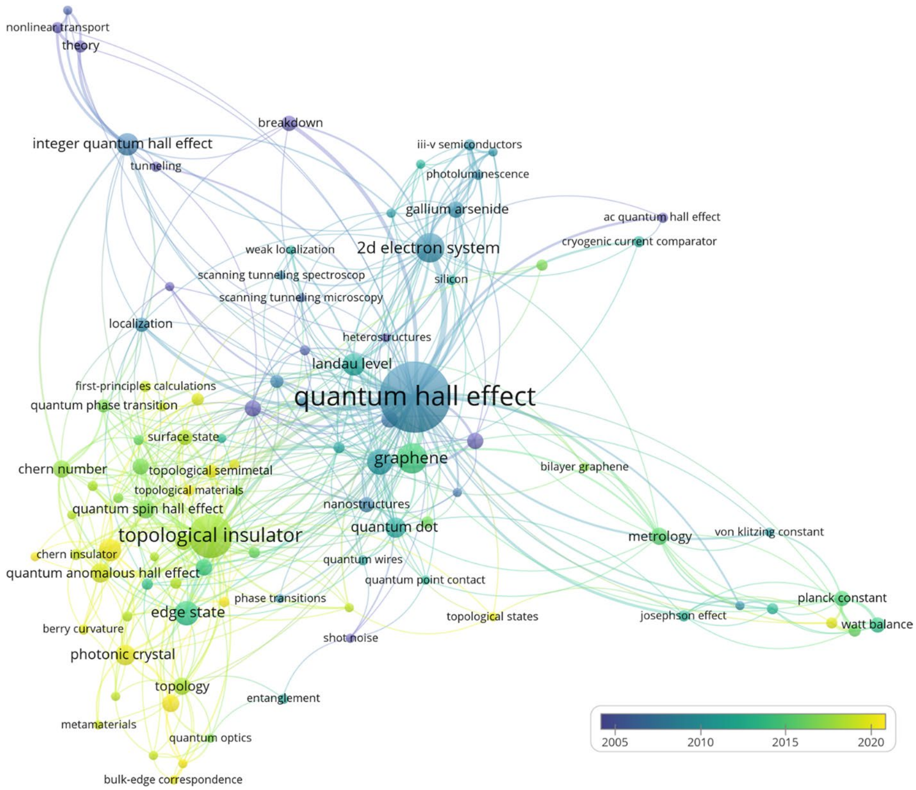

Fig. 2 Co-occurrence network of 96 author keywords that occur at least five times in the citing papers. The nodes are colored by the average publication year. An interactive version can be viewed at: https://s.gwdg.de/kAXUxo

A ‘topological insulator’ is characterized by special conductive edges/surfaces and an insulating bulk as a consequence of the material’s band structure—a quantum Hall sample is analogous.

Based on the keyword map in Fig. 2, we defined—driven by the intrinsic connections as described before—broader topics and defined WoS queries to capture the corresponding papers within the set of papers that cited the 1985 Physics Nobel Prize paper:

- Topological insulator: TS = (“Topological insulator$” OR “Topological phase$”)
- Graphene: TS = (Graphene OR Dirac)
- Fractional QHE: TS = ((Fractional SAME (Hall OR QHE)) OR “Electron Correlation$” OR “Composite Fermion$”)
- Metrology: TS = (Metrolog* OR “SI Units” OR “Watt Balance” OR “Kibble Balance” OR “Resistance Standard*”)

The annual number of papers for these topics within the set of papers that cited the 1985 Physics Nobel Prize paper is shown in Fig. 3. The figure clearly shows that the revival of

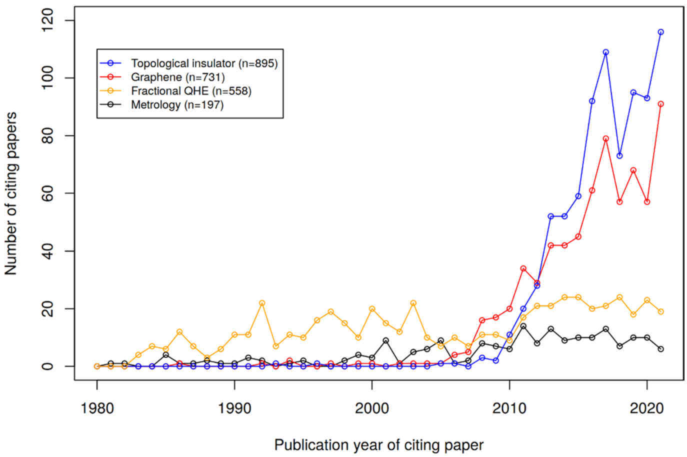

Fig. 3 Annual number of papers that cited the 1985 Physics Nobel Prize paper broken down by the main topics. The number of papers n in the legend includes the papers from the incomplete year 2022 although the graph excludes this year

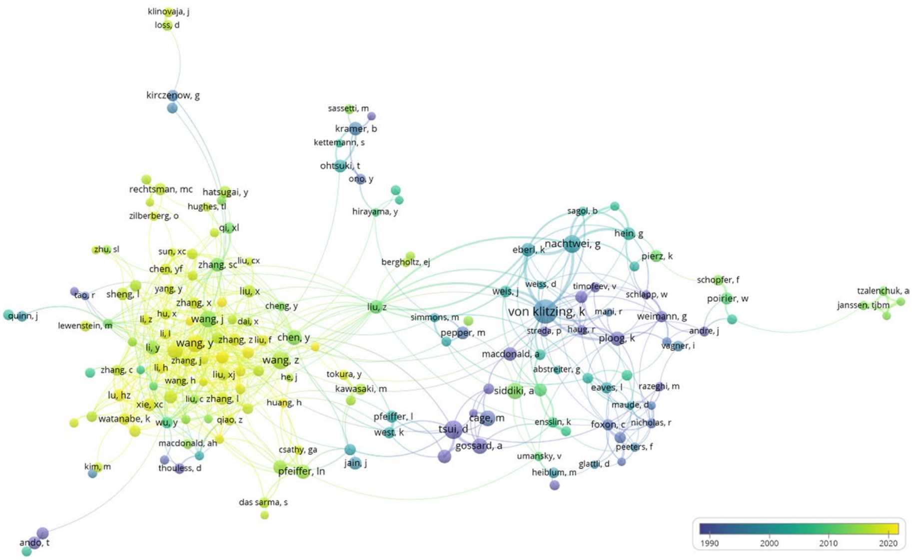

Fig. 4 Co-authorship network of the citing papers of those co-authors that appear at least ten times. Only the large component of 176 connected out of a total of 194 nodes is shown. The nodes are colored by the average publication year. An interactive version can be viewed at: https://s.gwdg.de/vzXWrI. The full network with all 194 nodes can be viewed at: https://s.gwdg.de/RiURUK

the 1985 Physics Nobel Prize paper is tied to the topics 'topological insulator' and 'graphene'. The rise of the topic 'graphene' appears before 'topological insulator', however, the latter now becomes dominant. With fluctuations in the past, after 2010 also the clustered keywords 'metrology' and 'fractional QHE' reach a moderate higher constant level, not present in the past.

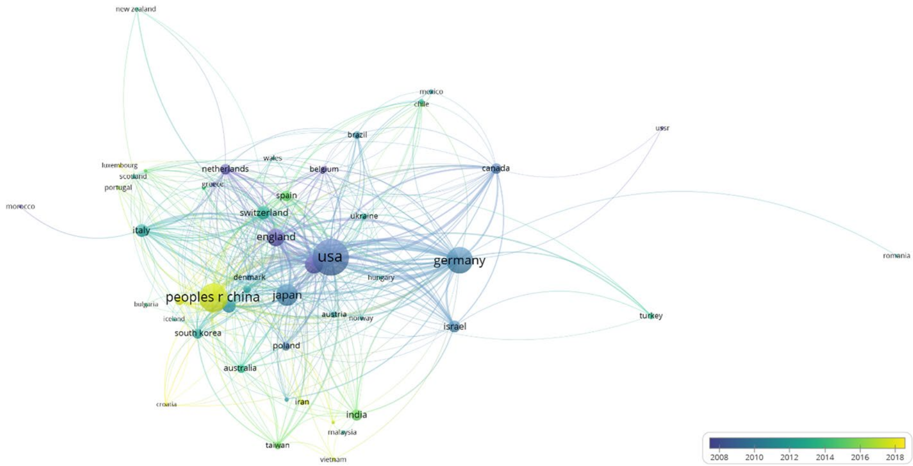

Fig. 5 Co-occurrence network of 51 countries that occur at least five times in the authors' affiliations of the citing papers. Slovenia is disconnected from the network and has been dropped. The labels 'fed rep ger' and 'germany' were merged. The nodes are colored by the average publication year. An interactive version can be viewed at: https://s.gwdg.de/haNfmH

Figure 4 shows the co-authorship network of the papers citing the 1985 Physics Nobel Prize paper. The nodes are colored by the average publication year. At first glance, the network breaks down by color into two subnetworks with only a few connections between them. One subnetwork—with older average publication year—is centered around Klaus von Klitzing reflecting his direct collaboration network. Each co-author node—directly linked to Klaus von Klitzing—has also its own small network, which has connections to networks isolated from Klaus von Klitzing. Here, also the persons that discovered the fractional quantum Hall effect appear. There is no link found to those (Andre Geim and Konstantin Novoselov who received the Physics Nobel Prize in 2010) demonstrating for the first time graphene as quantum Hall material. Actually, they do not appear in the co-authorship network in Fig. 4 at all because they have cited the 1985 Physics Nobel Prize paper less than five times. The second large subnetwork has significantly younger average publication years, which on the one hand might explain that co-authorships are disjoint, on the other hand that something new might have attracted attention. No clear identification of authors is possible due to the lack of clearly disambiguated author data. Thus, a further analysis of such a graph is not suitable.[1]

Figure 5 shows the co-occurrence network of 51 countries from the author affiliations of the papers citing the 1985 Physics Nobel Prize paper. The nodes are colored by the average publication year. The People's Republic of China is the largest contributor of recent publications.

The annual number of citing papers for the citing countries that cited the 1985 Physics Nobel Prize paper most frequently is shown in Fig. 6. The strongest increases in the number of publications that cited the 1985 Physics Nobel Prize paper per country are observed

[1] Striking is the node 'Liu Z', having several connections to both subnetworks. However, a manual inspection of the papers co-authored by 'Liu Z' in our dataset shows that the node is not a single person but seems to represent at least five different scientists, leading to a misleading artifact in this network representation.

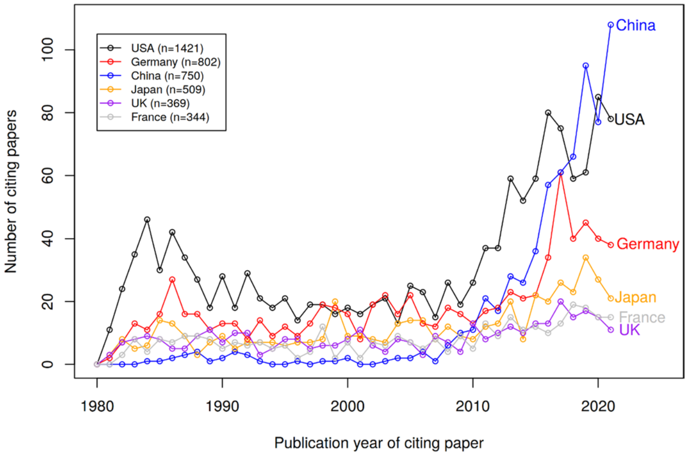

Fig. 6 Annual number of citing papers for the citing countries that cited the 1985 Physics Nobel Prize paper most frequently. The number of papers n in the legend includes the papers from the incomplete year 2022 although the graph excludes this year

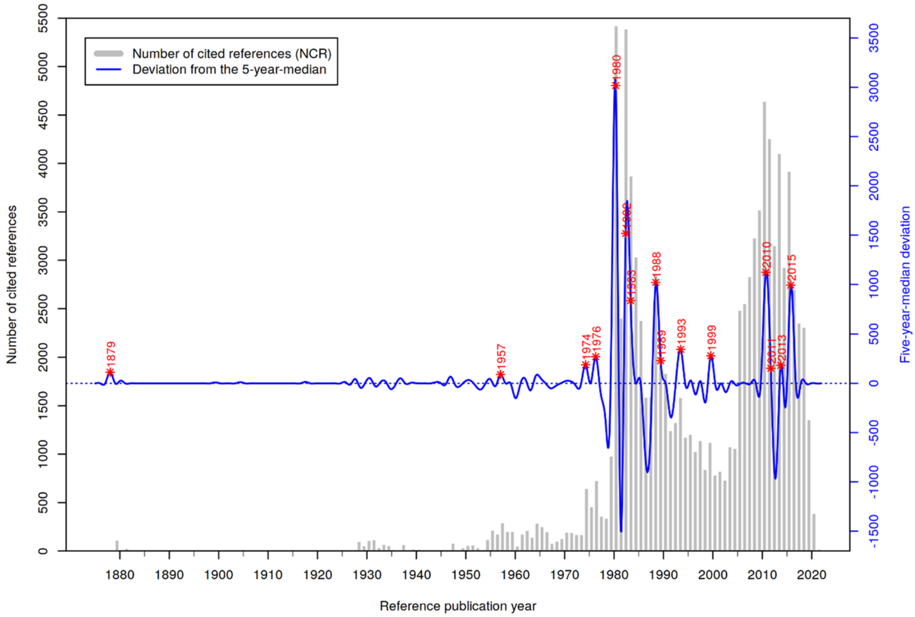

Fig. 7 RPYS-CO spectrogram. All references that contribute to this spectrogram are co-cited with the 1985 Physics Nobel Prize paper. An interactive version can be viewed at: https://s.gwdg.de/Fo8L77

for USA and—most recently—for the People's Republic of China, even dominating in 2021.

Figure 7 shows the RPYS-CO spectrogram for the 1985 Physics Nobel Prize paper as a marker paper. The graph depicts the number of papers co-cited with the marker paper

Table 1 Peak papers from RPYS-CO spectrogram in Fig. 7 ordered by the reference publication year (RPY) and number of co-cited references (NCR)

#CR	Co-cited reference	RPY	NCR	PERC_YR
1	Hall EH, 1879, *Am. J. Math.*, V2, P287, https://doi.org/10.2307/2369245	1879	113	1.00
2	Landauer R, 1957, *IBM J. Res. Dev.*, V1, P223, https://doi.org/10.1147/rd.13.0223	1957	111	0.38
3	Ando T & Uemura Y, 1974, *J. Phys. Soc. Jpn.*, V36, P959, https://doi.org/10.1143/JPSJ.36.959	1974	166	0.26
4	Hofstadter DR, 1976, *Phys. Rev. B*, V14, P2239, https://doi.org/10.1103/PhysRevB.14.2239	1976	316	0.43
5	Vonklitzing K et al., 1980, *Phys. Rev. Lett.*, V45, P494, https://doi.org/10.1103/physrevlett.45.494	1980	4179	0.77
6	Klitzing KV et al., 1980, *Phys. Rev. Lett.*, V45, P494, https://doi.org/10.1103/PHYSREVLETT.45.494	1980	510	0.09
7	Laughlin RB, 1981, *Phys. Rev. B*, V23, P5632, https://doi.org/10.1103/PhysRevB.23.5632	1981	868	0.36
8	Tsui DC et al., 1982, *Phys. Rev. Lett.*, V48, P1559, https://doi.org/10.1103/PhysRevLett.48.1559	1982	1574	0.29
9	Thouless DJ et al., 1982, *Phys. Rev. Lett.*, V49, P405, https://doi.org/10.1103/PhysRevLett.49.405	1982	1178	0.22
10	Laughlin RB, 1983, *Phys. Rev. Lett.*, V50, P1395, https://doi.org/10.1103/PhysRevLett.50.1395	1983	901	0.23
11	Haldane FDM, 1988, *Phys. Rev. Lett.*, V61, P2015, https://doi.org/10.1103/PhysRevLett.61.2015	1988	641	0.22
12	Buttiker M, 1988, *Phys. Rev. B*, V38, P9375, https://doi.org/10.1103/PhysRevB.38.9375	1988	348	0.12
13	Jain JK, 1989, *Phys. Rev. Lett.*, V63, P199, https://doi.org/10.1103/PhysRevLett.63.199	1989	298	0.14
14	Hatsugai Y, 1993, *Phys. Rev. Lett.*, V71, P3697, https://doi.org/10.1103/PhysRevLett.71.3697	1993	192	0.12
15	Halperin BI et al., 1993, *Phys. Rev. B*, V47, P7312, https://doi.org/10.1103/PhysRevB.47.7312	1993	152	0.10
16	Lilly MP et al., 1999, *Phys. Rev. Lett.*, V82, P394, https://doi.org/10.1103/PhysRevLett.82.394	1999	60	0.05
17	Nachtwei G, 1999, *Physica E*, V4, P79, https://doi.org/10.1016/S1386-9477(98)00251-3	1999	60	0.05
18	Kane CL & Mele EJ, 2005, *Phys. Rev. Lett.*, V95, https://doi.org/10.1103/PhysRevLett.95.226801	2005	586	0.24
19	Kane CL & Mele EJ, 2005, *Phys. Rev. Lett.*, V95, https://doi.org/10.1103/PhysRevLett.95.146802	2005	550	0.22
20	Bernevig BA et al., 2006, *Science*, V314, P1757, https://doi.org/10.1126/science.1133734	2006	620	0.24
21	Konig M et al., 2007, *Science*, V318, P766, https://doi.org/10.1126/science.1148047	2007	585	0.21
22	Hasan MZ & Kane CL, 2010, *Rev. Mod. Phys.*, V82, P3045, https://doi.org/10.1103/RevModPhys.82.3045	2010	938	0.20
23	Qi XL & Zhang SC, 2011, *Rev. Mod. Phys.*, V83, https://doi.org/10.1103/RevModPhys.83.1057	2011	674	0.16
24	Chang CZ et al., 2013, *Science*, V340, P167, https://doi.org/10.1126/science.1234414	2013	317	0.08
25	Rechtsman MC et al., 2013, *Nature*, V496, P196, https://doi.org/10.1038/nature12066	2013	254	0.06
26	Wu LH & Hu X, 2015, *Phys. Rev. Lett.*, V114, https://doi.org/10.1103/PhysRevLett.114.223901	2015	128	0.03
27	Aidelsburger M et al., 2015, *Nat. Phys.*, V11, P162, https://doi.org/10.1038/NPHYS3171	2015	124	0.03

Table 1 (continued)

#CR	Co-cited reference	RPY	NCR	PERC_YR
28	Yang ZJ et al., 2015, *Phys. Rev. Lett.*, V114, https://doi.org/10.1103/PhysRevLett.114.114301	2015	122	0.03
29	Xu SY et al., 2015, *Science*, V349, P613, https://doi.org/10.1126/science.aaa9297	2015	120	0.03
30	Susstrunk R & Huber SD, 2015, *Science*, V349, P47, https://doi.org/10.1126/science.aab0239	2015	113	0.03

The final column also shows PERC_YR values that indicate how much a certain co-cited reference is responsible for the individual peak as a function of their publication years. The numbers of co-cited references (NCR) are shown as gray bars. The five-year-median deviation is shown as a blue line. The co-cited papers represent the citation environment of the marker paper and are a suitable publication set for revealing booster papers and papers most important for subsequent research topics. The RPYS-CO is based on the idea that high peaks in the median deviations are hints to important publications for the analyzed publication set. Peaks in early reference publication years point to the historical roots of the analyzed research field. Outlier peaks are indicated by red stars and marked by red labels with their reference publication year (RPY). Table 1 lists the co-cited references that are mainly responsible for the peaks. The table also includes the RPY, the NCR values, and the PERC_YR values.

CR1 is the origin of what nowadays is known as (classical) Hall effect. Between 1925 and 1970, several small peaks appear in the data. For example, the pioneering work CR2 (1957) is identified, deriving the two-terminal resistance of a metallic conductor if localized scatterers are present. With a significantly larger peak, CR3 (1974) is obtained where the longitudinal and transversal (Hall) conductivity of a disordered two-dimensional electron system in a strong magnetic field was theoretically treated. The experiments on such a system led to the discovery by Klaus von Klitzing (CR5, CR6)[2] in 1980—now denoted as (integer) quantum Hall effect. With CR7 in 1981, very fundamental arguments were given why a quantized Hall conductance with high accuracy can indeed be expected in such a system. With CR12 in 1988, the microscopic picture of the integer quantum Hall effect based on one-dimensional chiral edge states, connecting the contacts in a multi-terminal device and enclosing an insulating bulk, was established. The review CR17 summarized the knowledge in 1999 on the electrically induced breakdown of the integer quantum Hall effect.

With CR8 in 1982 and CR10 in 1983 the fractional quantum Hall effect was established (for which the Physics Nobel Prize was awarded in 1998). As explanation, CR10 presented a variational wavefunction ansatz for an interaction electron system in presence of a strong magnetic field, which is protected by an energy gap against excitations. In 1989, CR13 introduced the concept of composite fermions (electrons with attached magnetic flux quanta) to explain a series of some fractional quantum Hall states by the integer quantum Hall effect of composite fermions. In 1993, CR15 developed in an extensive work the theoretical description and predicted various properties of an interaction electron system showing fractional quantum Hall states. In 1999, CR16 reported the unexpected observation of anisotropic vanishing longitudinal resistance with lowering the temperature in the magnetic field regime where still several Landau levels are present. Anisotropic electronic phases seem to evolve under such conditions.

CR4 in 1976 presented the eigenenergy spectrum of electrons in high magnetic fields where—in addition—a spatial periodic potential is seen by the electrons. In 1982, CR9 showed the respective calculation of the quantized Hall conductance for Bloch electrons using topological arguments. Based on that work, CR14 linked in 1993 the number of edge states expected in an integer quantum Hall sample with the so-called Chern number as a topological invariant of an infinite 2D Bloch electron system with applied magnetic field.

In 1988, CR11 predicted the principle existence of a quantum Hall effect without Landau levels (in the absence of an external magnetic field) by breaking the

[2] The marker paper appears as two different variants of the same cited reference because the automatic clustering did not recognize these two variants.

time-reversal symmetry in a ‘2D graphite’-like material. In 2005, CR18 studied theoretically the spin–orbit interaction in graphene, opening an energy gap in the semimetal, and claimed due to edge states the existence of a quantum spin Hall effect. CR19 related in 2005 the existence of the quantum spin Hall effect to specific topological properties of the band structure, analogous to what was done before with the Chern number for the integer quantum Hall effect. In 2006, CR20 proposed a narrow HgTe layer (‘quantum well’) embedded between CdTe to see the quantum spin Hall effect. This was experimentally realized in 2007 by CR21. In 2010, the instructive article CR22 reviewed the knowledge and prospects on topological insulators, i.e., materials where the bulk is insulating by an energy gap but—due to spin-orbital coupling—conductive states exist on their edges or surfaces. Conventional quantum Hall samples require an applied magnetic field to get a topological insulator. In 2011, CR23 also reviewed topological insulators and their experimental realizations and verifications, and discussed the general theory on topological insulators and superconductors. The quantum anomalous Hall effect—quantum Hall effect without applied magnetic field—was realized in 2013 by CR24 in a 2D topological insulator with built-in ferromagnetism.

The work CR25 extended in 2013 the concept of topological insulators to photonic crystals. In 2015, CR26 proposed and treated theoretically a dielectric honeycomb lattice as photonic crystal with a non-trivial topology. CR27 demonstrated in 2015 the measurement of the Chern number in an ultracold lattice of bosonic atoms. Also in 2015, CR28 proposed an acoustic version of a topological insulator with unidirectional sound propagation. In extending the concept of topological classification to non-insulating materials, in 2015 the existence of Weyl fermions as quasiparticles in a semimetal (TaAs) with specific topological properties has been experimentally shown by CR29. In CR30 (2015), a two-dimensional arrangement of coupled mechanical oscillators revealed the existence of phononic edge modes, expected for a mechanical topological insulator.

For analyzing the citation relations outside the set of co-cited papers, we retrieved the authors’ names and authors’ countries from all papers citing selected cited references from the WoS. From Fig. 1, we suppose that the renewed interest in the 1985 Physics Nobel Prize paper was sparked around or after 2000. CR18-CR22 were published between 2005 and 2010 and are responsible for at least 20% of the NCR values in the corresponding years (PERC_YR values are at least 0.2). Thus, we compared the authors’ names and authors’ countries of all papers that cited CR18-CR22 with the authors’ names and authors’ countries in the co-authorship map in Fig. 4. The papers citing CR18 (authors are Kane CL and Mele EJ) have three of the five most frequently occurring authors’ names in common with authors’ names in the co-authorship map in Fig. 4, i.e., Zhang SC, Liu F, and Wang J. This indicates that Zhang SC, Liu F, and Wang J gave substantial credit in their work to the earlier work by Kane CL and Mele EJ. Especially, Zhang SC and Wang J appear also with a rather old average publication year in the left subnetwork in Fig. 4. The papers citing CR19 (authors are Kane CL and Mele EJ) have Zhang SC as the most frequent co-author. This indicates that Zhang SC also played a pioneering role in the field. The papers citing CR20–CR22 also each have one of the five most frequent authors’ names in common with authors’ names in the co-authorship map in Fig. 4 (it is Zhang SC for CR20/CR21, and it is Wang J for CR22). The People’s Republic of China is the most frequent authors’ country and the USA is the second most frequent one for citing CR18, CR20, and CR22; the People's Republic of China is the second most frequent authors' country for CR19 and CR21. Here, the USA is the most frequent authors' country. Both, USA and the Peoples Republic of China, appear very prominently in the country co-occurrence map in Fig. 5. Not surprisingly, this indicates that authors from USA and the People's Republic of China played an important role in the field. We conclude from this overlap of topics, authors' names, and authors' countries between the citing papers of the1985 Physics Nobel Prize paper and citing papers of CR18-CR22 that CR18 and CR19 are the primary booster papers, and CR20-CR22 are secondary booster papers for the revival of the 1985 Physics Nobel Prize paper.

Discussion and conclusions

In order to answer the research questions that were stated in the introduction, we analyzed the annual citation profile of the 1985 Physics Nobel Prize paper, the topics, authors, and authors' countries of the citing papers. We also performed a co-citation analysis via RPYS-CO of the 1985 Physics Nobel Prize paper. The annual citation profile of this paper showed a renewed interest in its content since 2005, which seems to be related to the keyword topological insulators.

Comparing topics of rather frequently co-cited papers in the appropriate time period (in this case around 2005) pointed us towards likely candidates for booster papers. Further inspection of the authors' names and authors' countries increased the likelihood that these likely booster papers initiated the renewed interest in the 1985 Physics Nobel Prize paper. We found two primary booster papers—Kane and Mele (2005a) and Kane and Mele (2005b)—and three secondary booster papers—Bernevig et al. (2006), König et al. (2007), and Hasan and Kane (2010). All these booster papers deal with topological insulators. Thus, the renewed interest in the 1985 Physics Nobel Prize paper is (at least partly) due to the interest in topological insulators. It took a while for this field to boost up: The founding works were honored by the 2016 Physics Nobel Prize to D.J. Thouless, F.D.M. Haldane, and J.M. Kosterlitz. Especially, the works CR9 and CR11 from the 1980s highlighted the quantum Hall effect as a topological effect and were part of the justification for the Nobel Prize in 2016. This prize was triggered by the strongly rising interest in topological materials in the years before reflected also in the citation rise of the 1985 Physics Nobel Prize paper.

It is probable that this combined analyses of topic modeling, co-authorship analysis, and co-citation analysis is also successful in the case of other papers with a similarly unusual annual citation profile. Further work should apply the approach outlined here to other citation classics with similarly unusual annual citation profiles. The methodology proposed here might also be suitable to explain the renewed interest in publications with delayed recognition, also referred to as sleeping beauties (van Raan, 2004).

Appendix

See Table 2.

Table 2 Thesaurus for author keywords

Label	Replacement
Topological insulators	Topological insulator
Chern numbers	Chern number
Composite fermions	Composite fermion
Edge states	Edge state
Electron–electron interactions	Electron–electron interaction
Landau levels	Landau level
Photonic crystals	Photonic crystal
Quantum dots	Quantum dot
Quantum Hall effects	Quantum Hall effect
Semiconductors	Semiconductor
2-Dimensional electron gas	2d Electron system
2d Electron gas	2d Electron system
Two-dimensional electron gas	2d Electron system
Two-dimensional electron system	2d Electron system
Quantized Hall resistance	Quantum Hall effect
Quantum Hall	Quantum Hall effect
Dirac equation	Dirac particle
Dirac fermions	Dirac particle
Surface states	Surface state
Topological phases	Topological phase
Topological semimetals	Topological semimetal
Gaas	Gallium arsenide
Electron transport	X
Electronic structure	X
Electronic transport	X
Electrical transport	X
Hall effect	X
Longitudinal resistance	X
Magnetic field	X
Magnetism	X
Magnetoresistance	X
Magnetotransport	X
Quantum effects	X
Quantum transport	X
Shubnikov-de haas effect	X
Two-dimensional materials	X

The label X is removed from the dataset before final construction of the map

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Declarations

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References

Bernevig, B. A., Hughes, T. L., & Zhang, S.-C. (2006). Quantum spin Hall effect and topological phase transition in HgTe quantum wells. *Science, 314*(5806), 1757–1761. https://doi.org/10.1126/science.1133734

Birkle, C., Pendlebury, D. A., Schnell, J., & Adams, J. (2020). Web of science as a data source for research on scientific and scholarly activity. *Quantitative Science Studies, 1*(1), 363–376. https://doi.org/10.1162/qss_a_00018

Bornmann, L., Haunschild, R., & Leydesdorff, L. (2018). Reference publication year spectroscopy (RPYS) of Eugene Garfield's publications. *Scientometrics, 114*(2), 439–448. https://doi.org/10.1007/s11192-017-2608-3

Bornmann, L., & Haunschild, R. (2023). Reference publication year spectroscopy (RPYS) of papers published by Loet Leydesdorff: A giant in the field of scientometrics passed away. *Profesional de la información*, *32*(7), e320701. https://doi.org/10.3145/epi.2023.dic.01.

Garfield, E. (1977). Introducing citation classics: the human side of scientific reports. *Essays of an Information Scientist, 3*, 1–2.

Hasan, M. Z., & Kane, C. L. (2010). Colloquium: topological insulators. *Reviews of Modern Physics, 82*(4), 3045–3067. https://doi.org/10.1103/RevModPhys.82.3045

Haunschild, R. (2021). BibPlots: Plot functions for use in bibliometrics. R package version 0.0.8. Retrieved October 26, 2021, from https://cran.r-project.org/web/packages/BibPlots/index.html

Haunschild, R., Bauer, J., & Bornmann, L. (2019). Influential cited references in FEMS microbiology letters: lessons from reference publication year spectroscopy (RPYS). *FEMS Microbiology Letters*. https://doi.org/10.1093/femsle/fnz139

Haunschild, R., & Marx, W. (2019). *Discovering Seminal Works with Marker Papers*. Paper presented at the 8th International Workshop on Bibliometric-enhanced Information Retrieval, Cologne. http://ceur-ws.org/Vol-2345/paper3.pdf

Haunschild, R., & Marx, W. (2020). Discovering seminal works with marker papers. *Scientometrics, 125*(3), 2955–2969. https://doi.org/10.1007/s11192-020-03358-z

Kane, C. L., & Mele, E. J. (2005a). Quantum spin Hall effect in graphene. *Physical Review Letters, 95*(22), 226801. https://doi.org/10.1103/PhysRevLett.95.226801

Kane, C. L., & Mele, E. J. (2005b). ${Z}_{2}$ Topological order and the quantum spin Hall effect. *Physical Review Letters, 95*(14), 146802. https://doi.org/10.1103/PhysRevLett.95.146802

König, M., Wiedmann, S., Brüne, C., Roth, A., Buhmann, H., Molenkamp, L. W., & Zhang, S.-C. (2007). Quantum spin Hall insulator state in HgTe quantum wells. *Science, 318*(5851), 766–770. https://doi.org/10.1126/science.1148047

Leydesdorff, L., Bornmann, L., Comins, J., Marx, W., & Thor, A. (2016). Referenced publication year spectrography (RPYS) and algorithmic historiography: the bibliometric reconstruction of András Schumbert's Œuvre. In W. Glänzel & B. Schlemmer (Eds.), *András Schubert-A world of models and metrics. Festschrift for András Schubert's 70th birthday* (pp. 79–96). International Society for Scientometrics and Informetrics.

Marx, W. (2021). History of RPYS. Retrieved from https://figshare.com/articles/conference_contribution/History_of_RPYS/14910615
Marx, W., Bornmann, L., Barth, A., & Leydesdorff, L. (2014). Detecting the historical roots of research fields by reference publication year spectroscopy (RPYS). *Journal of the Association for Information Science and Technology, 65*(4), 751–764. https://doi.org/10.1002/asi.23089
Marx, W., Haunschild, R., Thor, A., & Bornmann, L. (2017). Which early works are cited most frequently in climate change research literature? A bibliometric approach based on Reference Publication Year Spectroscopy. *Scientometrics, 110*(1), 335–353. https://doi.org/10.1007/s11192-016-2177-x
Nobel Prize Outreach AB 2021. (1985). The Nobel Prize in Physics 1985. NobelPrize.org. Retrieved 26 October, 2021, from https://www.nobelprize.org/prizes/physics/1985/summary
R Core Team. (2018). R: A language and environment for statistical computing (Version 3.5.0). Vienna, Austria: R Foundation for Statistical Computing. Retrieved from https://www.r-project.org/
Seglen, P. O. (1992). The skewness of science. *Journal of the American Society for Information Science, 43*(9), 628–638. https://doi.org/10.1002/(SICI)1097-4571(199210)43:9%3c628::AID-ASI5%3e3.0.CO;2-0
Thor, A., Bornmann, L., & Haunschild, R. (2018a). CitedReferencesExplorer (CRExplorer) manual. Retrieved December 19, 2019, from https://andreas-thor.github.io/cre/manual.pdf
Thor, A., Bornmann, L., Marx, W., & Mutz, R. (2018b). Identifying single influential publications in a research field: New analysis opportunities of the CRExplorer. *Scientometrics, 116*(1), 591–608. https://doi.org/10.1007/s11192-018-2733-7
Thor, A., Marx, W., Leydesdorff, L., & Bornmann, L. (2016a). Introducing CitedReferencesExplorer (CRExplorer): A program for reference publication year spectroscopy with cited references standardization. *Journal of Informetrics, 10*(2), 503–515. https://doi.org/10.1016/j.joi.2016.02.005
Thor, A., Marx, W., Leydesdorff, L., & Bornmann, L. (2016b). New features of CitedReferencesExplorer (CRExplorer). *Scientometrics, 109*(3), 2049–2051. https://doi.org/10.1007/s11192-016-2082-3
Tukey, J. W. (1977). *Exploratory data analysis*. Addison-Wesley Publishing Company.
van Eck, N. J., & Waltman, L. (2010). Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics, 84*(2), 523–538. https://doi.org/10.1007/s11192-009-0146-3
van Eck, N. J., & Waltman, L. (2021a). VOSviewer goes online! (Part 1). Retrieved 26 October, 2021, from https://www.leidenmadtrics.nl/articles/vosviewer-goes-online-part-1
van Eck, N. J., & Waltman, L. (2021b). VOSviewer goes online! (Part 2). Retrieved 26 October, 2021, from https://www.leidenmadtrics.nl/articles/vosviewer-goes-online-part-2
van Raan, A. F. J. (2004). Sleeping beauties in science. *Scientometrics, 59*(3), 467–472. https://doi.org/10.1023/B:SCIE.0000018543.82441.f1
Vanderkam, D., Allaire, J. J., Owen, J., Gromer, D., & Thieurmel, B. (2018). Dygraphs: Interface to 'Dygraphs' interactive time series charting library. R package version 1.1.1.6. Retrieved August 19, 2021, from https://CRAN.R-project.org/package=dygraphs
von Klitzing, K. (2019). Essay: quantum Hall effect and the new international system of units. *Physical Review Letters, 122*(20), 200001. https://doi.org/10.1103/PhysRevLett.122.200001
von Klitzing, K., Dorda, G., & Pepper, M. (1980). New method for high-accuracy determination of the fine-structure constant based on quantized Hall resistance. *Physical Review Letters, 45*(6), 494–497. https://doi.org/10.1103/PhysRevLett.45.494
Yao, Q., Li, X., Luo, F., Yang, L. P., Liu, C. J., & Sun, J. (2019). The historical roots and seminal research on health equity: A referenced publication year spectroscopy (RPYS) analysis. *International Journal for Equity in Health, 18*(1), 15. https://doi.org/10.1186/s12939-019-1058-3