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A bibliometric study of the work of Rosalind E. Franklin (1920-1958)

Une étude bibliométrique des travaux de Rosalind E. Franklin (1920-1958)

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Article abstract

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A bibliometric study of the work of Rosalind E. Franklin (1920-1958)

Une étude bibliométrique des travaux de Rosalind E. Franklin (1920-1958)

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Abstract: After a short introduction to her life and work, we construct Rosalind Franklin's citation environment in the sense of Howard White. This environment consists of four groups of authors related to Franklin: her co-authors, those cited by Franklin, those co-cited with Franklin, and those citing Franklin. We further found two of her articles that can be considered as suffering from delayed recognition. The article ends with a complete bibliography of Franklin. Although she never received the Nobel Prize, she most certainly was "of Nobel Class."

Keywords: double helix, crystallography, citation environment, h-indices, delayed recognition

Résumé : Après une brève introduction à sa vie et à son œuvre, nous reconstruisons l'environnement de citation de Rosalind Franklin au sens de Howard White. Cet environnement se compose de quatre groupes d'auteurs liés à Franklin : ses coauteurs, ceux cités par Franklin, ceux co-cités avec Franklin et ceux citant Franklin. De plus, nous avons repéré deux de ses articles pouvant être considérés comme victimes de reconnaissance différée. L'article se termine par une bibliographie complète de Franklin. Bien qu'elle n'ait jamais reçu le prix Nobel, elle était très certainement « de calibre Nobel ».

Mots clés : double hélice, cristallographie, environnement de citation, indices h, reconnaissance différée

Introduction

This article has been written on the occasion of the 100th anniversary of the birth of Rosalind Franklin. We do not focus on her life or even her science, but mainly

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study her scientific achievements from a bibliometric point of view. We provide, in the words of Howard White (White 2000, 2001), an ego-centered picture of Franklin. In this way, we provide a longitudinal study of the acceptance of her ideas, first through publications and co-authors, and later through citations of her publications. For the definitions and more information about the used bibliometric notions, we refer the reader to Rousseau, Egghe, and Guns (2018).

Rosalind Franklin: A scientist's life

Rosalind Franklin was born on 25 July 1920 in London, England into an influential British-Jewish family. She died on 16 April 1958, in London.

Franklin made advances in three significant areas: the understanding of coal, the shape of the DNA (deoxyribonucleic acid) molecule, and the way RNA (ribonucleic acid) functions inside viruses. She is widely described as a brilliant experimentalist. She started higher education at Cambridge, from which she graduated in 1941. The British Coal Utilisation Research Association offered her a war-related research position in 1942, which led her to study the porosity of coal. Through this, she discovered the relationship between the fine constrictions in the pores of coals and the permeability of the porous space. From this she was able to classify coals and accurately predict their performance, for instance in gas masks—a fact recently recalled in *Nature* (2020). This research led to her Ph.D. in 1945. In 1947 she crossed the Channel and started working as a postdoctoral researcher in Méring's Laboratoire Central des Services Chimiques de l'État (Paris). It is there that she learned to apply X-ray crystallography to amorphous substances and became an accomplished X-ray crystallographer. Applying these techniques to coal and similar materials, she proposed the terms *graphitizing and non-graphitizing carbon* (Franklin 1951).

In 1951 she moved to King's College in London as a research associate, more precisely to the Medical Research Council's Biophysics Unit, directed by John Randall (Maddox 2002). Franklin, now working with Gosling as her doctoral student, started to apply her expertise in X-ray diffraction techniques to the structure of DNA. They discovered that there were two forms of DNA: at high humidity, the DNA fiber became long and thin; when it was dried it became short and fat (Maddox 2002). Franklin named these two forms "B" and "A" respectively (Klug 1968). In this way, Franklin and Gosling became very close to the solution of finding the structure of DNA. In fact, it was their X-ray diffraction data that put Watson and Crick on the way to the ultimate solution—actually of the B form—for the structure of DNA, and a Nobel Prize in 1962. Owing to disagreements with John Randall and more so with Maurice Wilkins (who shared the Nobel Prize in 1962), Franklin moved to Birkbeck College (London) in 1953.

There she started exploring RNA and worked with Aaron Klug, who had just earned his Ph.D. degree. Again, she used her skills as an X-ray crystallographer to study the structure of the tobacco mosaic virus, an RNA virus. On the suggestion of colleagues from Berkeley (California), she expanded her interests from plant viruses to animal viruses, in particular the poliovirus. After Franklin died in 1958, Klug succeeded her as a group leader, and he, Finch, and Holmes continued investigating the structure

of the poliovirus. Klug received the Nobel Prize in Chemistry in 1982 for "the structural elucidation of biologically important nucleic acid-protein complexes." Few doubt that if Rosalind Franklin had still been alive, she would have shared this Nobel Prize.

From this short overview of her work, we see that Franklin's research focused on three topics, moving from one to the other over time. At first, she worked with coal and carbonaceous material, then moved to diffraction studies of DNA and its structure, and finally, she started to study plant and animal viruses. For a full description of her life, we refer the reader to the book written by Brenda Maddox (Maddox 2002), and for a precise account of her role in the discovery of the structure of DNA we refer to the article written by Klug, Franklin's closest colleague at Birkbeck College, who inherited her notebooks (Klug 1968).

Franklin's obituary was written by John Desmond Bernal (Bernal 1958), her director at Birkbeck College. Bernal was not only a crystallographer and molecular biologist, but also one of the founders of the science of science through his work on the sociology of science (Bernal 1939). Franklin received posthumous recognition in many ways. In 2020 the Royal Mint minted a 50 pence coin in her honor. Moreover, several buildings and institutes are named after her.

Franklin's work seen through a bibliometric lens

Franklin published 55 documents, including her doctoral thesis and some short abstracts (see Appendix). Note that all counts of publications and citations provided in this article are complete or normal counts. These documents are spread over a period of 15 years: 1945-1959. Seven are published during the first 5 years, 20 during the second period, and 28 during the last. This shows that her scientific work was still increasing when she died prematurely. Of these 55 publications, 34 are classified as articles, 12 as (meeting) abstracts, 5 as notes, 2 as letters, one as editorial material, plus her doctoral thesis. These publications are mainly written in English, but seven are published in other languages: mainly French and German. One abstract is even written in Serbian. Her yearly publication h-index is 5 (Mahbuba and Rousseau 2013). This means that there are five years during which she published 5 or more documents: 1953 (8 publications), 1957 (7 publications), 1958 (7 publications), 1956 (6 publications), and 1955 (5 publications).

Nowadays (circa 2020) her (standard) h-index is 23. This h-index increased over the years in the way shown in Figure 1.

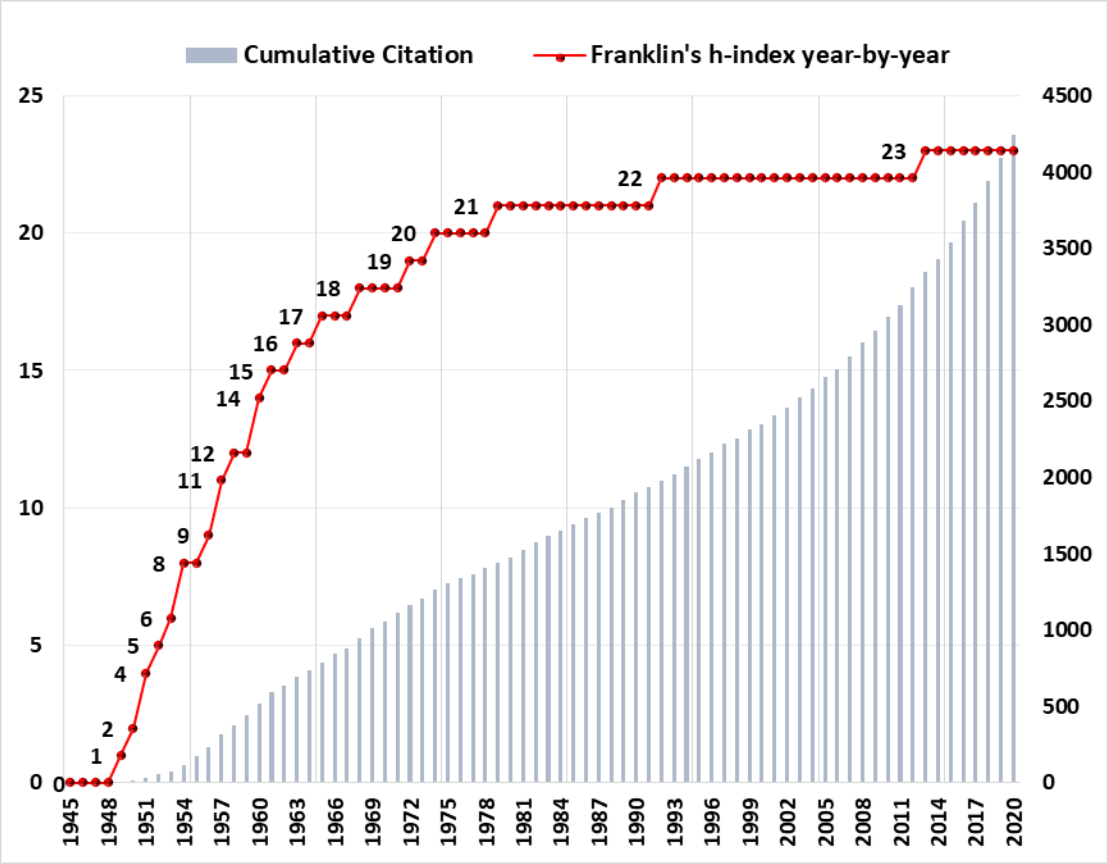

Figure 1: Increase of the total number of citations and the h-index of Rosalind Franklin (data from the WoS).

One can see that this increase is largely linear till approximately 1965 (already 7 years after her death). From then on, her h-index slowly reached a plateau. In this case, the h-index increased linearly, at least during her life, as assumed by Hirsch, when introducing the m-quotient (Hirsch 2005). The h-core includes about two-thirds of her (normal) articles, say citable documents.

Next, we have a look at her most-cited articles according to the Web of Science (WoS). These are shown in Table 1.

Citation	Times cited
Franklin, Rosalind E. 1951. "Crystallite Growth in Graphitizing and Non-Graphitizing Carbons." *Proceedings of the Royal Society A* 209 (1097): 196-218.	895
Franklin, Rosalind E., and Raymond G. Gosling. 1953. "Molecular Configuration in Sodium Thymonucleate." *Nature* 171 (4356): 740-741.	656
Franklin, Rosalind E. 1951. "The Structure of Graphitic Carbons." *Acta Crystallographica* 4 (3): 253-261.	573
Franklin, Rosalind E., and Raymond G. Gosling. 1953. "The Structure of Sodium Thymonucleates Fibres. I. The Influence of Water Content." *Acta Crystallographica* 6 (8-9): 673-677.	348

Franklin, Rosalind E. 1950. "The Interpretation of Diffuse X-ray Diagrams of Carbon." *Acta Crystallographica* 3 (2): 107-121.	322

Table 1: The five most-cited articles written by Rosalind Franklin (from WoS as of December 2020)

Remarkably, this list includes mainly her earlier work. No article from her Birkbeck period is included. The reason for this is probably the fact that she started a new line of inquiry, finished by Klug and his colleagues after her premature death (getting him a Nobel Prize). The second article in Table 1 is the one published in *Nature*, together with the famous Watson-Crick article (Watson and Crick 1953). As published, it was considered to be supporting evidence for the Watson-Crick one.

We note that among Franklin's publications, meeting abstracts are not or rarely cited, see Appendix for the exact numbers. This corresponds with the observations made in Hu and Rousseau (2013). Her research was mainly published in the following journals: *Acta Crystallographica* (7 articles and 7 other contributions), *Nature* (7+2), *Biochimica et Biophysica Acta* (4+3), and the *Transactions of the Faraday Society* (3+3).

Franklin's citation environment

By the term "citation environment' we follow White's schema consisting of four groups of authors related to the author under investigation (the ego) (White 2000, 2001). These are: the co-authors, those providing the ego's citation identity (the ego's citees), the citation image (the ego's co-citees), and the citation image makers (citing the ego).

Co-authors

Beginning with the co-authors, we found 14 different co-authors. The most important ones are shown in Table 2.

Co-author	In articles (including edited books)	In other publications	Relation to Franklin
Klug, A.	9	3	Started as a post-doc at Birkbeck College; co-worker
Gosling, R. G.	5	2	Research student at King's College London
Holmes, K. C.	4	1	Colleague at Birkbeck College
Finch, J. T.	3	0	Research student at Birkbeck College, hired by Franklin

Table 2: Franklin's most-important co-authors

Citees

Next, we come to Franklin's citation identity: this is the set of authors cited at least once by the ego. For this, we need the complete reference lists of all Franklin's

publications. This was easy for those publications included in the Web of Science. We tried to collect all other publications to read their reference lists. Unfortunately, we could not find two abstracts. As abstracts by Franklin usually have no reference list, the data in the next tables are almost certainly not influenced by this gap. Unsurprisingly, she cited herself the most. When an author is cited more than once in one of Franklin's reference lists this is counted as often as there are different publications by this author cited.

Authors	Times referenced
Franklin, R.E.	100
Schramm, G.	38
Bernal, J. D.	24
Watson, J. D.	23
Crick, F. H. C.	22

Table 3: Top five scientists cited the most in Franklin's publications (her citation identity)

Table 4 shows the articles that are most cited by Franklin. These refer to her research on viruses. Note that it was not unusual at that time to read and refer to articles written in German.

Publications	Times used
Watson, James D. 1954. "The Structure of Tobacco Mosaic Virus: I. X-ray Evidence of a Helical Arrangement of Sub-units Around the Longitudinal Axis." *Biochimica et Biophysica Acta* 13: 10-19.	16
Franklin, Rosalind E. 1955. "Structure of Tobacco Mosaic Virus." *Nature* 175 (4452): 379–381.	14
Bernal, John D., and Isidor Fankuchen 1941. "X-ray and Crystallographic Studies of Plant Virus Preparations: I. Introduction and Preparation of Specimens II. Modes of Aggregation of the Virus Particles." *The Journal of General Physiology* 25 (1): 111-146.	13
Schramm, Gerhard. 1947. "Über die Spaltung des Tabakmosaikvirus und die Wiedervereinigung der Spaltstücke zu höhermolekularen Proteinen. I. Die Spaltungsreaktion." *Zeitschrift für Naturforschung B* 2 (3-4): 112-121.	10
Schramm, Gerhard. 1947. "Über die Spaltung des Tabakmosaikvirus und die Wiedervereinigung der Spaltstücke zu höhermolekularen Proteinen: II. Versuche zur Wiedervereinigung der Spaltstücke." *Zeitschrift für Naturforschung B* 2 (7-8): 249-257.	9

Table 4: Top five most-used articles

Co-citees

Now we determine the authors most-cited together with Franklin. According to the WoS, the following 8 authors are each co-cited at least 750 times with Franklin: Watson, J. D. (1,573 times), Wilkins, M. H. F. (940 times), Schramm, G. (819 times),

Oberlin, A. (814 times), Pauling, L. (785 times), Klug (770 times), Fraenkel-Conrat (762 times) and Crick (761 times). This ego author co-citation network is shown in Figure 2 using VOSviewer (van Eck and Waltman, 2010, 2014).

Following on from the author co-citation map we show Franklin's article co-citation map (Figure 3) also constructed through VOSviewer (van Eck and Waltman 2010, 2014). We set the minimum number of citations of a cited reference as 20; 317 articles meet this threshold. In Figure 3, a node represents a document. Its size indicates its citation frequency. The thickness of a line between two nodes (a link in the network) represents the number of co-citations of the two documents. In Figure 3, only lines for co-citation counts greater than or equal to 5 are shown. Figure 3 clearly shows the three research interests of Franklin: coal and carbonaceous material (left), diffraction studies of DNA (upper right), and viruses (lower right).

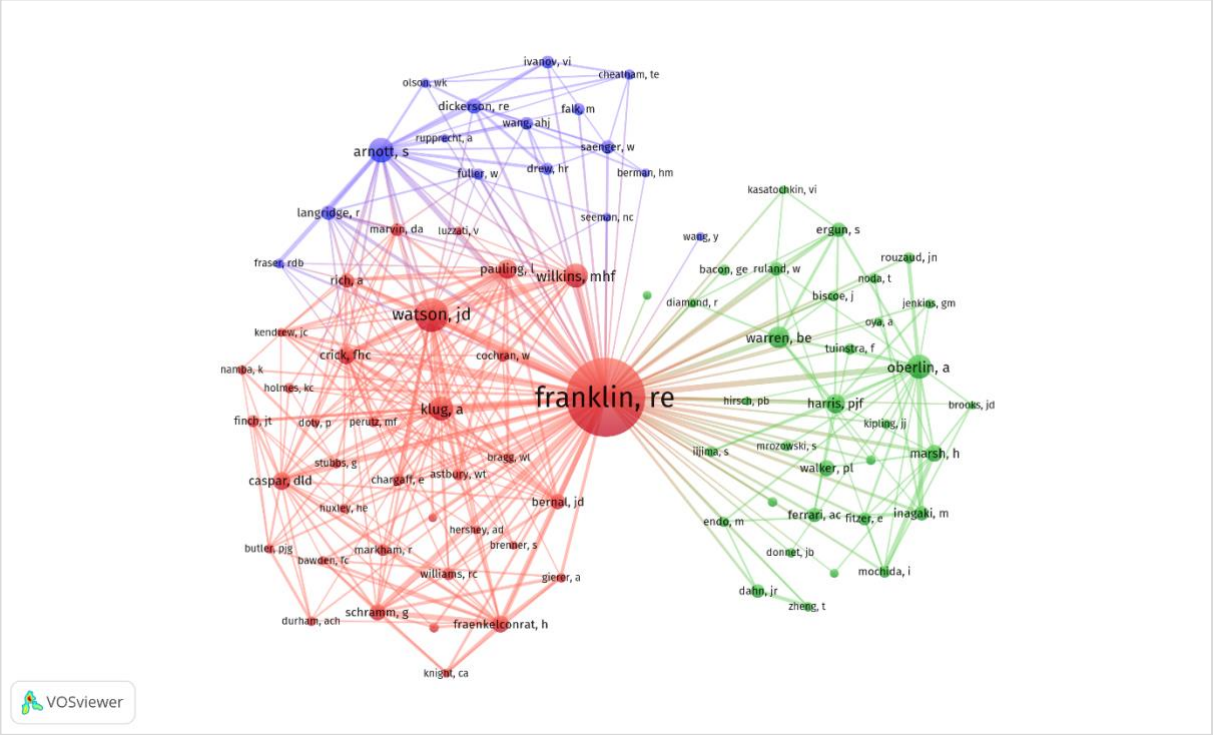

Figure 2: Author co-citation map of Rosalind Franklin

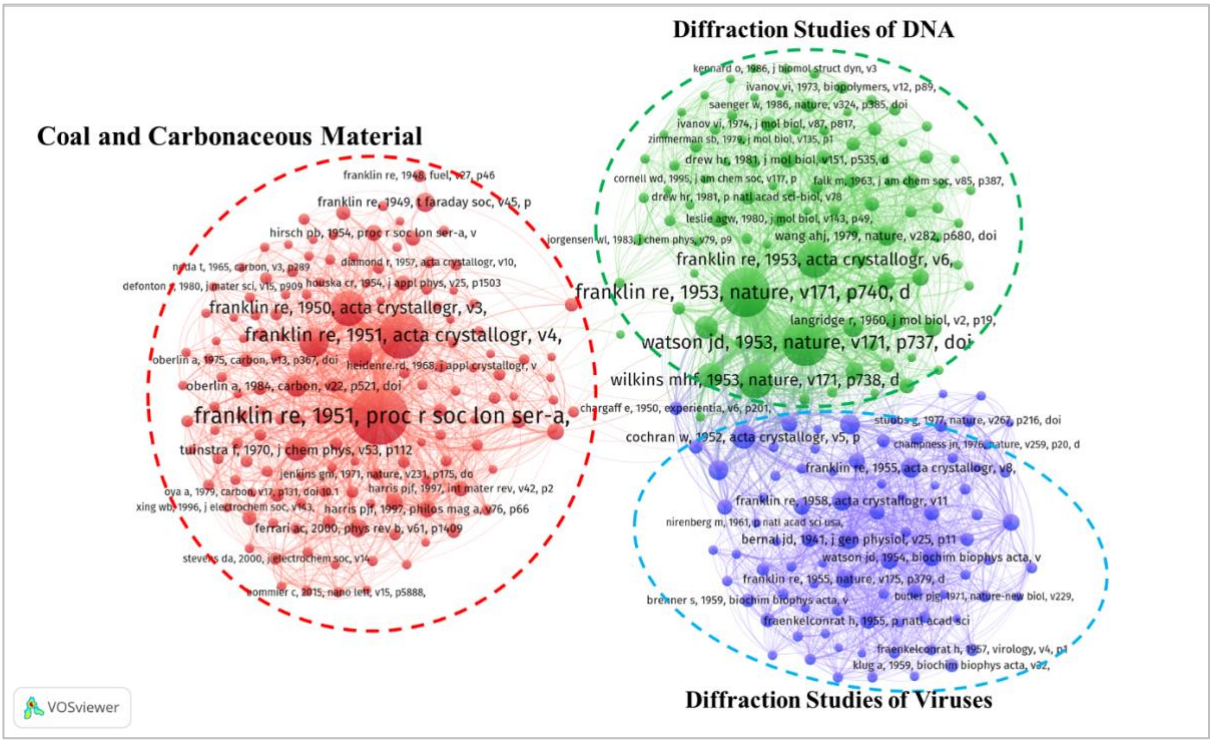

Figure 3: Franklin's article co-citation network

Citing Franklin (the ego): The citation image makers

Franklin received more than 11,500 citations in the Web of Science. By this, we mean that there are 11,500 citation instances, where an article with five authors citing at least one article by Franklin counts for five citation instances.

The authors with the most articles (in the Web of Science) citing at least one article by Franklin are shown in Table 5. Note that we count articles citing Franklin at least once. Nationality refers to the country in which this scientist worked, not the country of birth. Aaron Klug, for instance, was born in Lithuania, educated in South Africa, but did his important work in England (UK). Gerald Stubbs, who finished the research line on fiber diffraction analysis of tobacco mosaic viruses started by Franklin, was born in Australia and worked for many years in Germany before moving to the USA. The last column of Table 5 mentioned the first year in which this scientist cited Franklin, according to the WoS. Of course, Rosalind Franklin features among the scientists citing her work.

Rank	Author	Nationality	No. times citing	First year
1	Klug, Aaron	UK	33	1955
2	Stubbs, Gerald	USA	32	1974
3	Oberlin, Agnes	France	31	1967
4	Franklin, R. E.	UK	27	1949
5	Rouzaud, Jean-Noel	France	24	1982
6	Rupprecht, Allan	Sweden	23	1970
7	Walker Jr., P. L.	USA	20	1953
8	Finch, John T.	UK	19	1957
9	Holmes, Kenneth C.	UK	19	1956

10	Do, Duong D.	Australia	17	1996

Table 5: Authors citing Franklin the most (from Web of Science)

Delayed recognition

We proposed (Rousseau 2018) the following method and definition of an article suffering from delayed recognition, also known as a *sleeping beauty* (van Raan 2004) or *hibernator* (Hu et al. 2018). The three parts: delayed, recognition, and the actual value are operationalized as follows. For the delayed part, we started studying citations ten years after their publication. "Recognition" is operationalized as belonging to the top 1% most-cited publications (at the moment of the investigation, denoted as T) among all WoS publications published in the same year as the target publication. Finally, a fuzzy membership function is determined (Rousseau 2018), based on ideas from Ke et al. (2015), and Du and Wu (2018). This membership function, as calculated at time *T*, is denoted as *DR(T)*, and defined as:

$$DR(T) = Max_{10 \leq t \leq T}\{0, K(t)\} \quad (1)$$

Here *t* denotes time since publication and *K(t)* is defined as

$$K(t) = \frac{2}{(t-1)C(t)} S(t) \quad (2)$$

where *C(t)* is equal to the cumulative number of received citations at the beginning of the year *t*, and

$$S(t) = \sum_{n=0}^{t} \left(\frac{C(t)}{t} n - C(n) \right) \quad (3)$$

The resulting membership value is always situated between 0 and 1. As an ad hoc threshold, we suggested the value 0.333, obtained for linear growth in citations. For more details, we refer the reader to Rousseau (2018). Taking all this into account we found that Franklin's two most-cited articles (noted in Table 6 and Table 7) can be considered to be hibernators. Among these two we have her *Nature* paper published alongside the Watson-Crick one. That this paper suffered delayed recognition is not surprising given the fact that even the Watson-Crick paper was not an immediate success, see further. Figures 4 and 5 illustrate the fact that these two papers suffered from delayed recognition.

Year *t*	*K(t)*	Year *t*	*K(t)*	Year *t*	*K(t)*	Year *t*	*K(t)*	Year *t*	*K(t)*
1951	0.000	**1965**	0.054	**1979**	0.141	**1993**	0.126	**2007**	0.245
1952	0.000	**1966**	0.067	**1980**	0.106	**1994**	0.140	**2008**	0.265
1953	0.000	**1967**	0.090	**1981**	0.113	**1995**	0.157	**2009**	0.278
1954	0.250	**1968**	0.130	**1982**	0.128	**1996**	0.169	**2010**	0.295
1955	0.000	**1969**	0.225	**1983**	0.122	**1997**	0.195	**2011**	0.300
1956	0.028	**1970**	0.252	**1984**	0.111	**1998**	0.193	**2012**	0.314
1957	-0.116	**1971**	0.261	**1985**	0.102	**1999**	0.214	**2013**	0.322

1958	-0.091	**1972**	0.253	**1986**	0.102	**2000**	0.218	**2014**	***0.338***
1959	-0.074	**1973**	0.240	**1987**	0.080	**2001**	0.226	**2015**	***0.345***
1960	0.008	**1974**	0.233	**1988**	0.077	**2002**	0.227	**2016**	***0.361***
1961	0.151	**1975**	0.232	**1989**	0.079	**2003**	0.221	**2017**	***0.383***
1962	0.126	**1976**	0.204	**1990**	0.101	**2004**	0.233	**2018**	***0.402***
1963	0.067	**1977**	0.178	**1991**	0.120	**2005**	0.231	**2019**	***0.424***
1964	0.080	**1978**	0.156	**1992**	0.121	**2006**	0.240	**2020**	***0.437***

Table 6: K-values, formula (2), for Franklin, R. E. (1951). Crystallite Growth in Graphitizing and Non-graphitizing Carbons

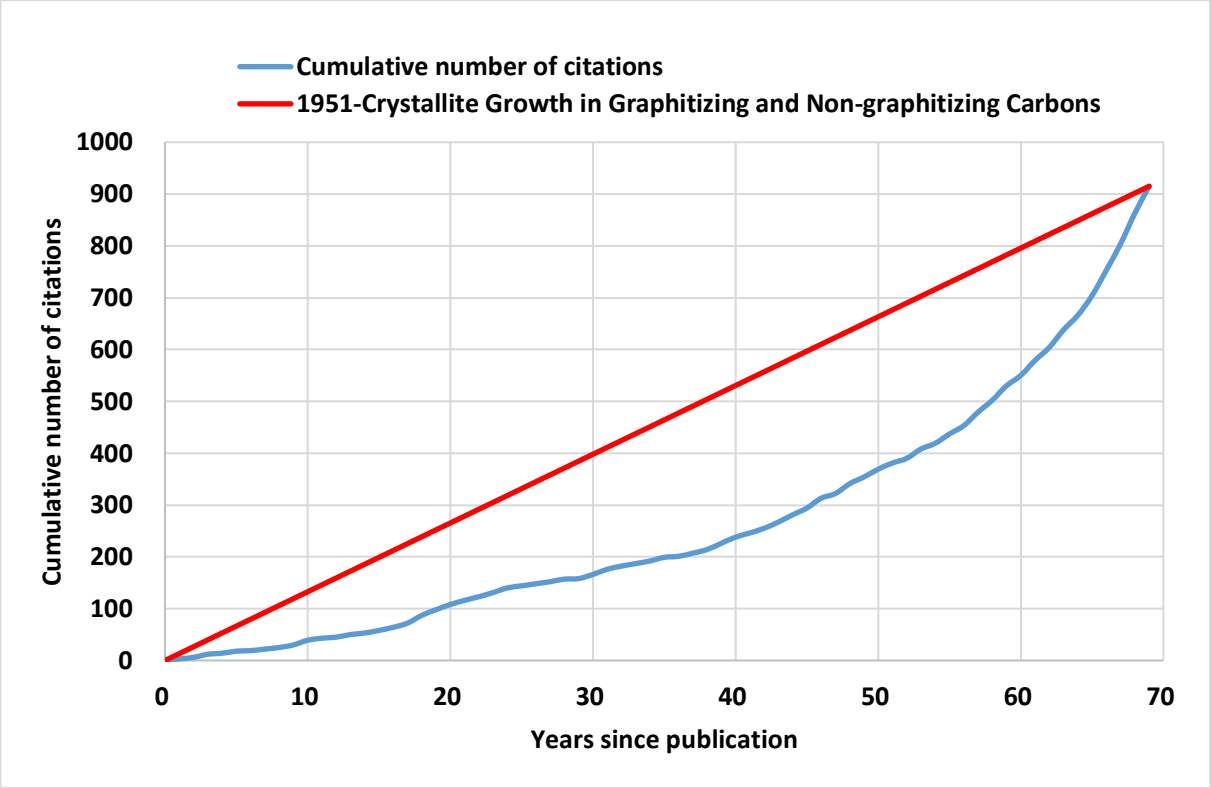

Figure 4: Cumulative citation curve of Franklin, R. E. (1951) and recognition line

Year *t*	*K(t)*	Year *t*	*K(t)*	Year *t*	*K(t)*	Year *t*	*K(t)*
1953	0.000	**1970**	-0.156	**1987**	-0.177	**2004**	0.123
1954	0.000	**1971**	-0.175	**1988**	-0.166	**2005**	0.154
1955	0.040	**1972**	-0.204	**1989**	-0.124	**2006**	0.160
1956	-0.063	**1973**	-0.179	**1990**	-0.132	**2007**	0.187
1957	-0.135	**1974**	-0.168	**1991**	-0.124	**2008**	0.232
1958	-0.183	**1975**	-0.193	**1992**	-0.110	**2009**	0.256
1959	-0.174	**1976**	-0.192	**1993**	-0.084	**2010**	0.280
1960	-0.211	**1977**	-0.225	**1994**	-0.068	**2011**	0.296
1961	-0.143	**1978**	-0.231	**1995**	-0.041	**2012**	0.322
1962	-0.194	**1979**	-0.237	**1996**	-0.029	**2013**	***0.349***
1963	-0.171	**1980**	-0.241	**1997**	-0.023	**2014**	***0.361***
1964	-0.225	**1981**	-0.223	**1998**	-0.008	**2015**	***0.386***
1965	-0.248	**1982**	-0.197	**1999**	-0.004	**2016**	***0.406***

1966	-0.178	**1983**	-0.165	**2000**	-0.010	**2017**	***0.418***
1967	-0.186	**1984**	-0.154	**2001**	-0.001	**2018**	***0.424***
1968	-0.148	**1985**	-0.154	**2002**	0.011	**2019**	***0.438***
1969	-0.118	**1986**	-0.153	**2003**	0.098	**2020**	***0.435***

Table 7: K-values, formula (2), for (Franklin and Gosling 1953). Molecular Configuration in Sodium Thymonucleate

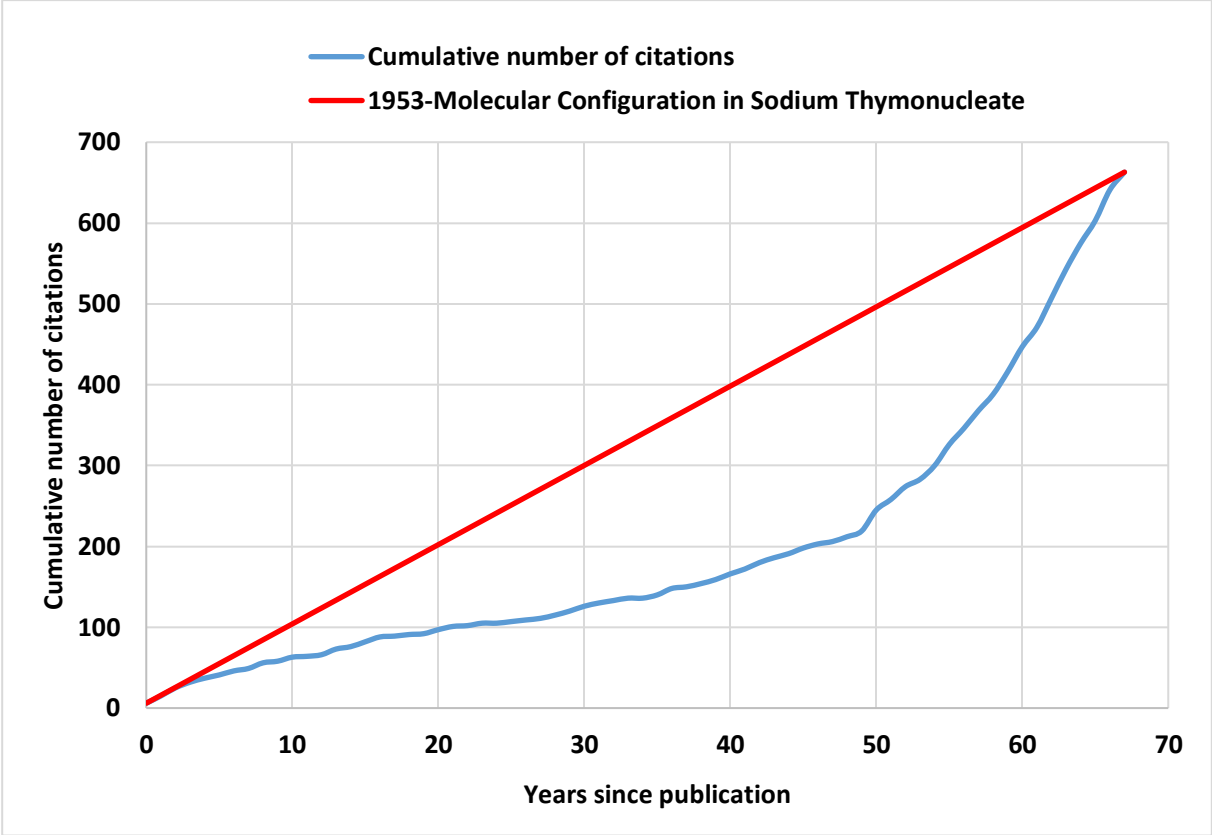

Figure 5: Cumulative citation curve of (Franklin and Gosling 1953), and recognition line

Some remarks

In this section, we provide some extra information related to Franklin's publications. When using complete-normalized fractional counting (giving each contributing author a score of 1/n when there are n authors in total), Franklin has 37.33 publications, namely 20.83 articles (in journals or edited books) and 16.5 other ones. As Franklin often published on her own, or at most with three co-authors, this reduction in publications (from 55 to 37.22) is much smaller than for most currently active researchers. Franklin published 16 articles with at least 16 references (and not 17). This means that her reference h-index is 16 (Liang and Rousseau 2010).

Conclusion

On the occasion of the 50th anniversary of the famous Watson-Crick article (Watson and Crick 1953) the journal *Nature* published a series of articles related to this

discovery. In this issue, it was observed that the discovery of the double helix structure took some time before it was recognized as essential in the study of heredity. Its reception among scientists was rather lukewarm. Consequently, during the 1950s, the article was rarely cited in *Nature* (Olby 2003). This author noted that the DNA double helix was not taken seriously until a mechanism for its involvement in protein synthesis began to take shape. In another article in this same series Helen Pearson (Pearson 2003) quotes Gasser and other scientists stating that the double helix is not a static structure but that it regularly morphs itself into alternative shapes and structures such as a propeller shape, and other so-called G-quadruplex structures.

Franklin's publication list and her article co-citation network show her main research interests. Chronologically they are coal and carbonaceous material, diffraction studies of DNA and viruses. The frequency and patterns of citations vary by research topic.

Although she never received the Nobel Prize, Rosalind Franklin most certainly was "of Nobel Class" (Garfield 1987).

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Appendix: A complete bibliography of Rosalind Elsie Franklin (1920-1959)

All citations were collected in the WoS in October 2020. We added the type of publication and the number of citations to the bibliographical data. The last articles in the list were published posthumously.

1945

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1948

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1949

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Moreover, we found the following items related to Rosalind Franklin. For reasons mentioned below, we do not consider them as part of her bibliography.

Herz, R. H., Hirsch, P. B., Peiser, H. S., Cox, E. G., Franklin, R. E., Hardwich, I. H., Wooster, W. A., Rieck, G. D., Arndt, U. W., Bacon, G. E., Cochran, W., Thewlis, J., Wilson A. J. C., and Andrews, K. W. 1954. "Summarized Proceedings of a Conference on X-Ray Analysis - London, November 1953." *British Journal of Applied Physics* 5 (December): 417-425. Franklin is mentioned just once, so this cannot be considered a Franklin publication, although her name is mentioned among the authors (discussants).

"Early work on Tobacco Mosaic Virus." 1958. Contribution in the Session on Viruses and Nucleic Acids at the Annual Autumn Conference of the X-ray Analysis Group of the Institute of Physics held in London on 16 and 17 November 1956. *British Journal of Applied Physics* 9: 1-12. This is a report of a meeting in which her contribution is mentioned.