École Polytechnique Fédérale de Lausanne

The 1927 Solvay Conference

A turning point in history of modern physics ?

Final Report

History and the digital
DH-412

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1 Introduction

The fifth Solvay Conference has today indubitably a particular aura. Indeed, the photograph that was taken at this conference (shown in figure 1) is probably one of the most famous picture in the physics domain. This picture looks like it was containing all important names of that time, that are now almost all associated with physics principles : Schrödinger's cat, Heisenberg incertitude principle, Lorentz transformation, Planck's constant, Dirac bracket notation, Ehrenfest theorem, Pauli matrices, Brillouin zone, Bragg's plane, Compton effect, Bohr model, without fogretting Einstein whose importance in the common mind is not to be demonstrated anymore.

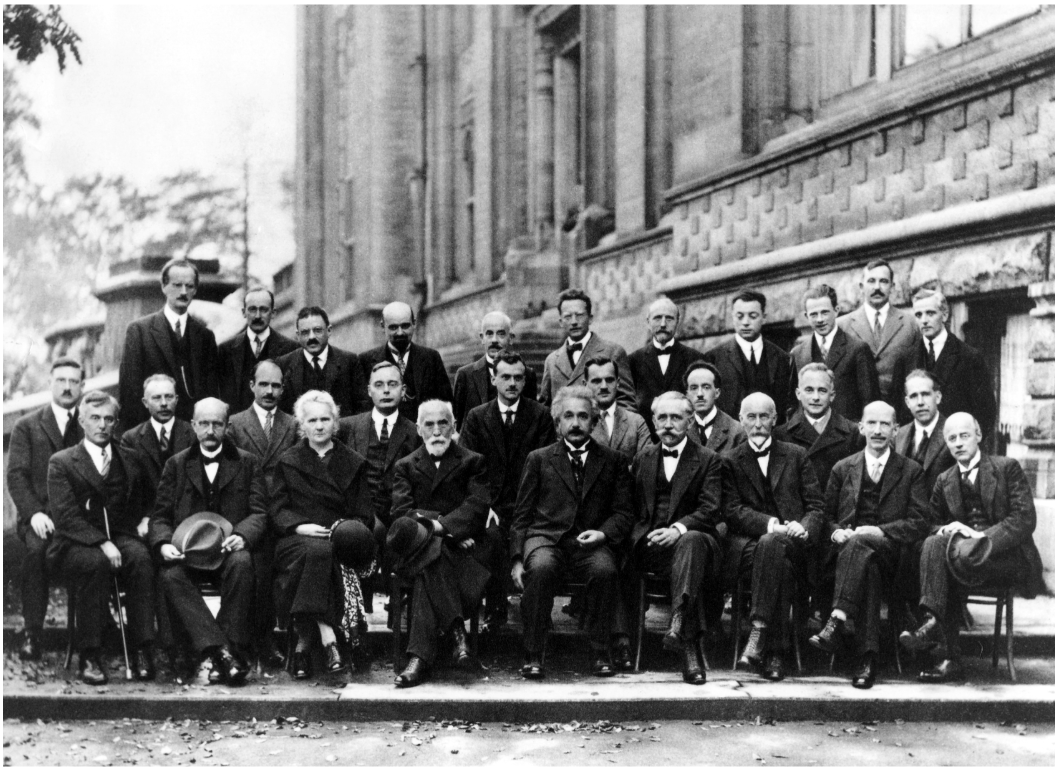


FIGURE 1: Fifth conference participants, 1927. Institut International de Physique Solvay in Leopold Park. [1]

The fifth Solvay Conference on Physics was held from 24 to 29 October 1927; the topic was *Electrons and Photons*, where the world's leading physicists gathered to discuss the newly formulated quantum theory. There are 29 physicist attended the fifth Solvay Conference: Auguste Piccard, Émile Henriot, Paul Ehrenfest, Édouard Herzen, Théophile de Donder, Erwin Schrödinger, JE Verschaffelt, Wolfgang Pauli, Werner Heisenberg, Ralph Fowler, Léon Brillouin, Peter Debye, Martin Knudsen, William Lawrence Bragg, Hendrik Anthony Kramers, Paul Dirac, Arthur Compton, Louis de Broglie, Max Born, Niels Bohr, Irving Langmuir, Max Planck, Marie Curie, Hendrik Lorentz, Albert Einstein, Paul Langevin, Charles-Eugène Guye, CTR Wilson and Owen Richardson [1]. The leading figures were Albert Einstein and Niels Bohr. Seventeen of the 29 attendees were or would become Nobel Prize winners, including Marie Curie, who was the only one to have won in two distinct scientific fields [2].

The aura of this conference was also probably caused by the different laudatory testimonies by the physicists themselves, as these examples :

> "[...] I enjoyed this particular conference. I think it has been the most memorable one which I have attended for the subject which was discussed was of such vital interest and I learned so much."
> W.L. Bragg to A. Solvay, 3 November 1927 [3].

> "It was the most stimulating scientific meeting I have ever taken part in."
> M. Born to C. Lefébure, 8 November 1927 [3].

or because some others physicists that seemed to not agree with the quality of the exchanges :

> "The confusion of ideas reached its peak."
> P.Langevin [4].

even if this last example might have been said on second degree.

With this context in mind, the purpose of this project is to analyze the 29 physicists attending the conference using a data-driven approach as opposed to a traditional physics perspective and quantitatively assess whether the conference is as significant as it appears.

We intend to analyze the similarities and differences of these attendees and their relationships with each other by first collecting information such as biographies and publications of these physicists and then using quantitative measurements and network analysis. In addition, we intend to describe the impact of this conference on the physics community by analyzing the number and keywords of publications and keywords before and after the conference.

2 Secondary Literature

2.1 Solvay Conferences

Two books were mainly used to have sources about the Solvay Conferences themselves.

The first one was *Quantum theory at the crossroads: reconsidering the 1927 Solvay conference*, by Guido Bacciagaluppi and Antony Valentini, which should be more considered as a physics book, but in which the first chapter gives a large historical context to the particular fifth conference [5]. The second is *The Solvay Conferences on Physics* by Jagdish Mehra [6]. Since Mehra is a historian of sciences, this reference seems closer to our own field.

2.2 Prosopography

In the 1970s, historian, Lawrence Stone gives the classical definition of prosopography: investigating the common background characteristics of a group of actors in history through a collective study of their lives. Stone pointed out prosopography tackles one of the basic problems in history, to help explain the intellectual movements in the society[7, p.48].

Prosopography is an effective approach to researching the history of science. A recent prosopographical study by Camille Akmut, *Social conditions of outstanding contributions to computer science : a prosopography of Turing Award laureates* [8], combines statistical analysis to reveal the social status of the award winners and how it contributes to their achievements. Similarly, Our project focuses on the elite physicists attending the fifth Solvay conference with many variables of their lives and explore the connections between them.

3 Data

The Solvay conference was held in 1927, and the majority of participants were active in the early twentieth century, before the advent of the Internet. As a result, the digital resources related to the conference and the physicists who attended were insufficient. Although some of the most renowned physicists, such as Einstein and Bohr, have complete online archive datasets, most physicists lack complete digitalized biographical and publication archives. There is no single dataset containing all the desired information. Consequently, the first step of this project is to collect the necessary data and construct our dataset.

Our primary data sources are the pages from the American Institute of Physics(AIP) [9] and The Academic Family Tree. AIP contains the biographies of nineteen physicists out of 29. Wikidata was used to compile another set of biographical data. The Academic Family Tree website generates academic genealogies of physicists based on mentoring relationships and collects their publications and educational backgrounds, but not for all attendees in the conference. Wikipedia and Google Scholar are used to complete missing profiles and publications. We also use existing archives and secondary literature to manually validate the facts we've collected.

Our final data set consists of two parts: biography data and publication data. The biography data includes biographical information for all 29 conference attendees in 14 columns, including their birth date, death date, place of birth, educational background, employment, collaborators, advisors, and subjects. We also collect categorical information from the biography and description file, such as whether or not they won the Nobel Prize and whether or not they gave a lecture at the conference. The publication data contains 556 metadata entries from 25 attendees (except Émile Henriot, Édouard Herzen, Paul Langevin, and Jules-Émile Verschaffelt) between 1921 and 1933, including authors, titles, years, and journals or publishers. [1]

4 Methods

In the article *The Craft of Elite Prosopography*, Jacob A. Lunding et al. suggest using relational methods like Multiple Correspondence Analysis (MCA) and Social Network Analysis (SNA) to construct the data to make a more "descriptive assemblages" of the study [10].

4.1 Multiple Correspondence Analysis

MCA is a statistical method for analyzing a population's categorical characteristics in a table[11]. As we build our dataset, we identify a lot of structuring information that helps us describe the features of the group of physicists. There are eleven separate binary columns for twenty-nine participants. These include things like who won the Nobel Prize before or after the conference, what their roles were of this conference, and who was invited to give scientific talks. With the projection in low-dimension, MCA is good at identifying which category has more frequency than others in a particular population. Given that not all participants have access to the same degree of detail, MCA handles incomplete data reasonably well, as missing columns do not affect the outcome. With the result of MCA, we can gain a general understanding of how categorical variables are related.

[1] The data and code is availible in `https://github.com/RuiaRui/HD_project`

4.2 Social Network Analysis

A direct view of the connections between individuals within a group is provided by social networks. It broadens the scope of MCA's relative abstract analysis. SNA is based on data that has well-defined relationships. The data can have various types of relationships. We identify academic partnerships such as co-author and collaborator relationships, student and advisor relationships, position appointment and recommendation interactions, and so on. Within a group, social networks can both show the most central characters and uncover lesser-known actors. The results of social networks need interpretation based on contextual knowledge from secondary literature.

5 Results and Discussion

5.1 Prosopography and Social Networks

Observing the timeline of the twenty-nine physicists (shown in figure 2), we notice that twenty-six hold a doctorate in relevant fields, fifteen had won the Nobel Prize in Physics, and three had won the Nobel Prize in Chemistry. Hendrik Antoon Lorentz, born in 1852, was the oldest in this group, and he was the chairman of the Solvay Conference from the first in 1911 to the fifth in 1927. Marie Curie was the only one who won both Nobel Prize in Physic and Chemistry among the participants. Pauli, Heisenberg, and Dirac were the youngest, with birth years in 1900, 1901, and 1902.

As a result of the preliminary research, we are interested in the geographical origins and the movements of the participants. As we already know most of them had doctorate in Physics and later became professor, we decide to focus on the places where they obtained their Ph.D. and the countries of employment. The results are shown in table 1, 2, and 3. There are several things worth noticing in this section of analysis. Maria Curie was born in Poland but went to France for her Ph.D. study. Max Born was born in Wroclaw, Poland, which belonged to German Empire at the time. Germany had the most diversity in hosting PhD student, besides people born here, physicists from Austria, the Netherlands, Poland, and the USA had all obtained their doctorate in Germany. When it comes to employment, the number of people resided in German speaking regions decreases significantly. No one worked in Austria and only half of people studied in Germany still worked there. Those who obtained PhD in France continued their academic careers there. Less known physicists worked in Belgium were close related to the Solvay family and the Solvay institute[5]. Herzen and Guye were members of Solvay Institute. Henriot was known as one of the organizer of physics conferences of the solvay institute and Verschaffelt served as a science secretary because of his multilingual talent in French, German and English.

Except , only four became full professor later than 1927. Eight of the fifteen Nobel Prize in Physics were awarded before the year 1927(including). Another five Nobel Prizes were awarded within 5 years until 1933. American physicist Arthur Holly Compton and Scottish physicist Charles Thomson Rees Wilson were the laureates in 1927. Erwin Schrödinger and Paul Dirac won the prize together in 1933.

The MCA analysis result is shown in Figure 3, where we input several categorical binary variables to discover the relationship inside them. The eleven categorical binary variables are shown on the top right of the diagram. The diagram reflects the relationship through the position of different catalogues and the physicists' points. Many points overlap because there are only eleven categories, but this demonstrates the similarity of these scientists' biographies. The point representing the column 'Won Nobel Prize in Chemistry After Conference' is located at the right of the diagram, far from the general public, as are Peter Debye and Irving Langmuir, two chemists. This is because the fifth Solvay meeting was predominately physical, and despite the fact that the elemental radioactivity studied by these chemists contributed to the theme of the meeting to some extent, they were more isolated from the other participants. The position of these three points in the diagram can also be utilized to verify the plausibility of the MCA results. The

Country of birth	Counts
Austria	3
Belgium	3
Denmark	2
England	4
France	4
Germany	3
Netherlands	3
Poland	2
Scotland	1
Switzerland	2
USA	2

TABLE 1: Country of Birth Count Results

Country Obtained PhD	Counts
Austria	2
Belgium	2
Denmark	2
England	3
France	5
Germany	6
Netherlands	1
Switzerland	4
USA	1
No PhD	3

TABLE 2: Country Obtained PhD Count Results

Employment Country	Counts
Belgium	4
Denmark	4
England	5
France	5
Germany	3
Netherlands	3
Switzerland	3
USA	2

TABLE 3: Employment Country Count Results

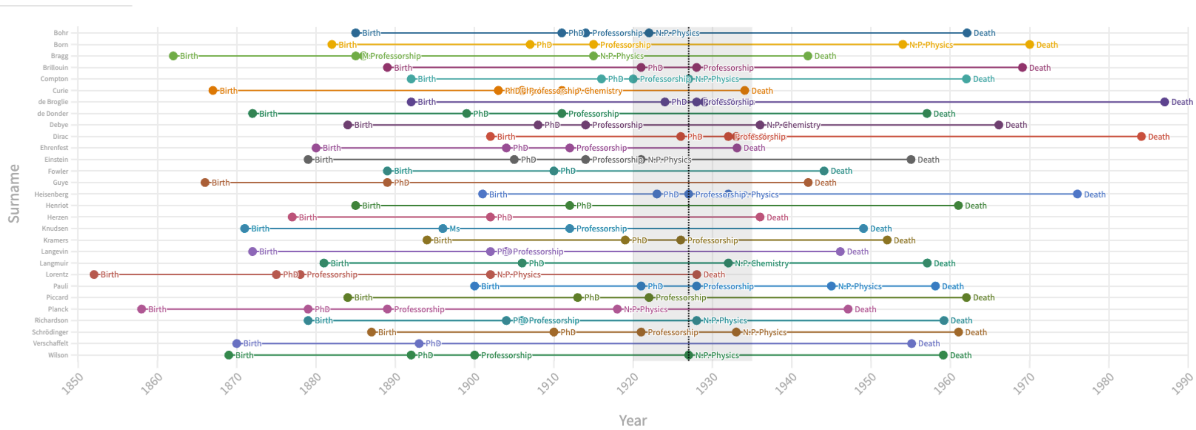


FIGURE 2: Timeline of the participants in the fifth Solvay Conference
Interactive version can be accessed through: https://go.epfl.ch/solvaytimeline

diagram also shows that Einstein, Lorentz, Madame Curie, Langevin, and Bohr, who were well-established physicists at the time, are clustered in the upper-left corner. At the same time, Pauli, Heisenberg, and others who had recently completed their PhD are located in the lower portion of the diagram. And nodes in the right area, such as Piccard, Henriot, Herzen and Verschaffelt can be reconigized as "outlier of the conference", since they are either Belgians affiliated with the Solvay Institute, representatives and guest scholars of the Solvay family, or the chemists previously mentioned. Their purpose of attendance was likely to witness or help take notes rather than participate in the discussion. This would also explain why we could not locate very detailed publication information on a significant number of them.

We generate two network (see in Figure 4) to analyse their relationship. The figure 4(a) shows the relationship inside the attendees group, where the nodes are the participating physicists classified by their primary subject, and the links are the academic connections previously stated in the method section 4.2. We can see from the plot that Niels Bohr can be linked to Heisenberg, Pauli and Kramers, his students and assistants, who worked together with Max Born (connected with Heisenberg) on Quantum mechanics during that period, and as Bohr supporters in the famous Bohr-Einstein debate. At the same time, Hendrik Lorentz and Paul Ehrenfest connected Bohr and Einstein in this network, Lorentz was the chairman of this Solvay conference, and Paul Ehrenfest was a great teacher and a pioneer of quantum theory, whose research inspired Einstein's General Relativity. Other interesting relationships, such as

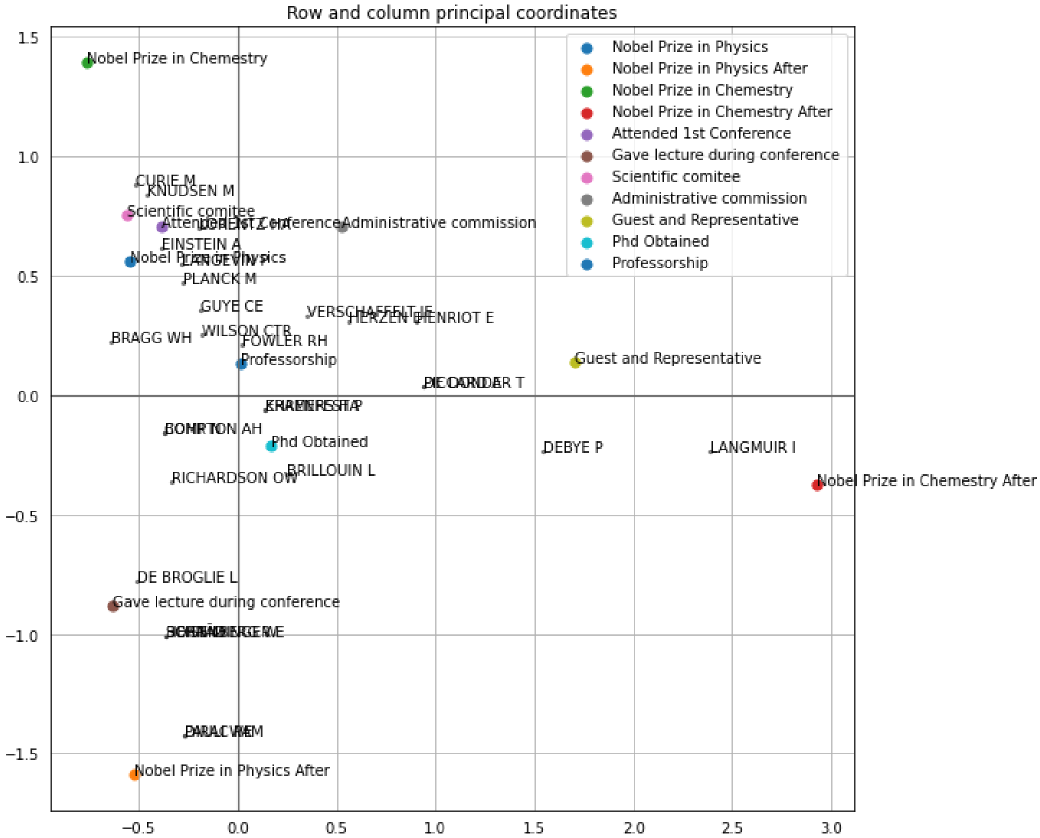
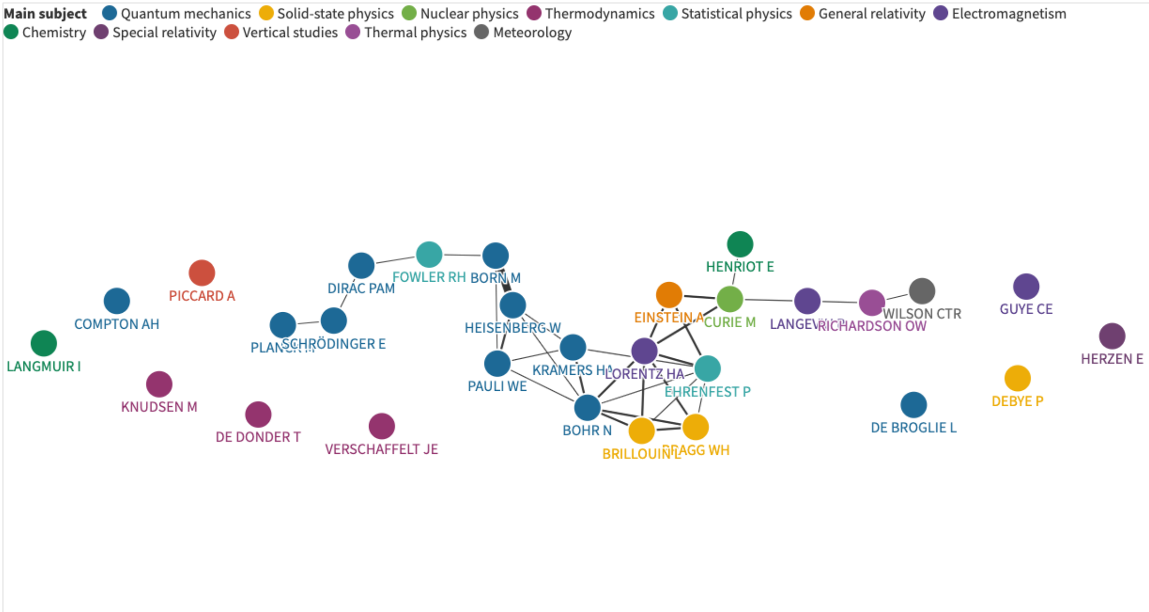


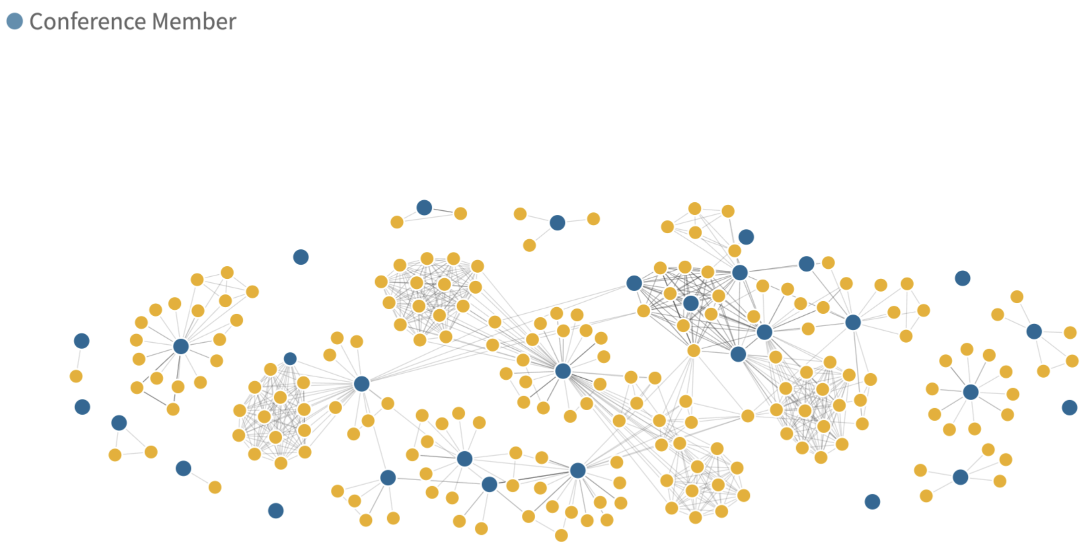
Figure 3: The MCA result with nine catelogical binary variables

Erwin Schrödinger and Paul Dirac, who were both awarded the Nobel Prize in Physics together five years after the conference, are also represented in the figure by the co-author relationship link. We also investigated when these relationships were formed, and almost all of them were formed before this conference. Further, corroborated by the content of the secondary literature, we can conclude that most of the participants already knew each other before this meeting, started to exchange letters or academic collaborations, and the purpose of this meeting was not a friendship or a chance to learn about other people's research, but a chance for a group of excellent physicists to sit down together and meet face to face to to analyze and discuss their research results.

Moreover, Figure 4(b) depicts all co-author relationships and is not limited to those within the group of participants. We wish to examine the degree of collaboration among these participating physicists in a more extensive network. This network can also reflect the collaboration among the physicists at that time. The graph shows that Irving Langmuir was the most collaborative one, whose research was conducted at the General Electric Company in the USAfollowed by Paul Ehrenfest and William Henry Bragg. We also find that even among the most influential physicists at the Solvay Conference, few were able to collaborate across circles, as illustrated by the figure. After the First World War, many scientists began to use nationality or position regarding the war as one of the criteria for cooperation. The third and fourth Solvay conferences refused to invite German and Austrian scientists, except for Ehrenfest[5]. This fifth Solvay conference was the first one after World War I in which German scientists were permitted to participate, thanks to Einstein's protest against the German scientists being barred from refusing to attend the previous conference [12]. Iaria, Schwarz and Waldinger's research [13] proved the similar idea that the subsequent boycott against Central scientists severely interrupted international scientic cooperation.



(a) relationship inside the attendees group.
Interactive version can be accessed through: https://go.epfl.ch/solvayrelashionship

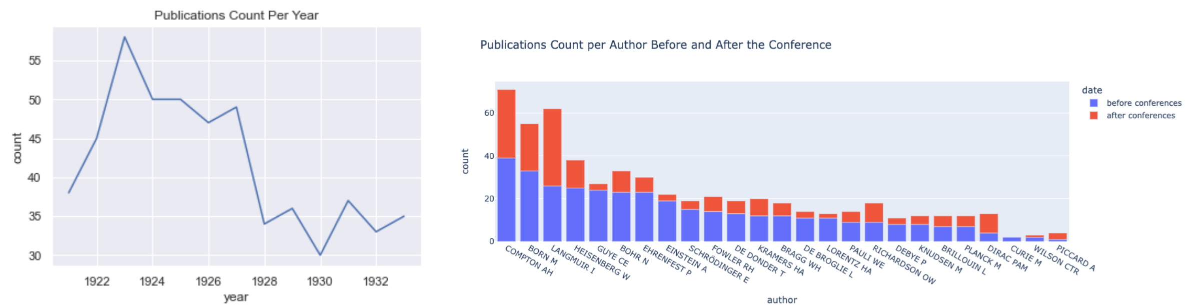


(b) co-author relationship including others.
Interactive version can be accessed through: https://go.epfl.ch/solvaycoauthorrelashionship

FIGURE 4: Social Network Analysis

5.2 Analysis the Impact of the Conference

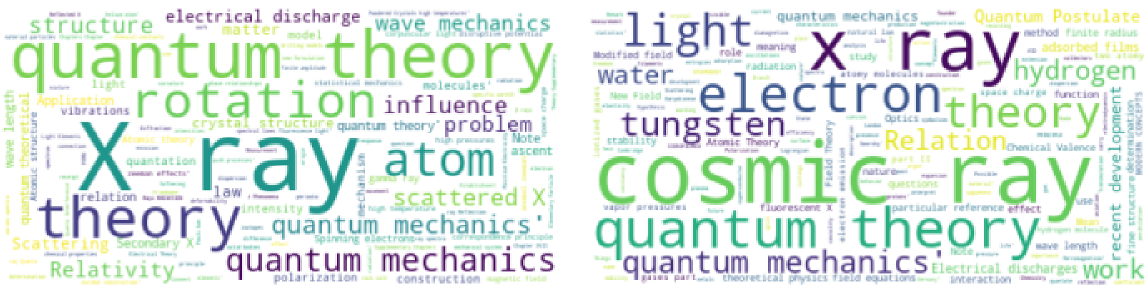
To determine the impact of this conference, we compared the number and topics of publications before and after the conference, and the results are depicted in the figures 5 and 6. Figure 5(a) shows that total publications decreased after the conference, and figure 5(b)shows that several more prolific physicists published fewer papers after the conference. According to figure 2, most physicists who attended the conference had already lived more than half of their lives, so it is understandable that they became less



(a) Publication count per year during 1921-1933

(b) Publication count per author Before and After the conference

FIGURE 5: Changes in the number of publications before and after the Solvay Conference



(a) Word Cloud of Publication keywords before Conference

(b) Word Cloud of Publication keywords after Conference

FIGURE 6: Changes in the topic of publications before and after the Solvay Conference

productive after the event. Another possible explanation is that before the conference was the beginning of the development of quantum physics. Various new theories, formulas, and interpretations accompanied the development of the papers. In contrast, after the conference, quantum physicists began to look for experimental evidence for the theories and evaluate and argue about the ideas, which may have decreased the number of papers. Moreover, it can be seen in figure 6 that the keywords of the papers before and after the conference did not change significantly; words such as *X-ray* and *quantum theory* continue to be the most frequently used keywords in their papers. Inferring from the published papers of these physicists, we conclude that the Fifth Solvay Conference had little impact on their research directions.

5.3 Citations : Qualitative Analysis

From our initial project, one main idea of network construction had to be left behind. It was the project of building a network with physicists that did significantly cite each others in their publications. Indeed, one observation had to be made : citations in scientific publications were unfortunately not as systematic at that time as they are nowadays. Therefore, a network constructed on this basis would have been poorly connected both in terms of number of edges than in terms of connection relevance.

This was however an instructive observation on habits of that time and it revealed itself as an interesting point to investigate qualitatively in a specific example. For this sake, we chose to look at one important scientific paper of that period : *Can quantum-mechanical description of physical reality be considered complete?* published by A. Einstein, B. Podolsky and N. Rosen in 1935 [14]. Even if this publication is slightly posterior to the fifth Solvay Conference, it seems nevertheless representative of the same period and the existence of a response by N. Bohr in an article with the exact same name clearly anchor both of them in this context [15].

The first point to mention about these two papers is the fact that Einstein's one does not contain any citation at all and the answer by Bohr only cite the first one and another paper by Bohr himself. This observation is symptomatic of the poor presence of formal citations, as we know nowadays, within scientific publications. The idea of this analysis, was to look for informal citations in these two papers or for situations where citation would be almost mandatory today, for example if the author mention the name of another scientist.

Regarding other physicists names, two of them appears in Bohr's paper, in the context of physical concepts that took their names. They are "de Broglie relation between momentum and wave-length" and "Heisenberg's general principle" [15, p. 697]. What is surprising to our contemporary eyes is that the first concept was introduced in 1924 [16] and the second one in 1927 [17], ie. respectively eleven and eight year before Bohr's publication. This indicates that these concepts were quickly taken for granted by the community and it was not needed to guide the reader to another reference. Maybe the acceptation of these principles was acquired during conferences as Solvay ones.

6 Limitations

6.1 Problems with Data Collecting

For biographical data, there are inconsistencies and some absence of information. For most participants, their education history follows the naming convention of BSc, Master/MSc, and Ph.D./ Doctorate. It can be different for those who obtained their degree in England. William Henry Bragg graduated in 1884 with a "Part I degree" and in 1885 with a "Part II degree." Similarly, Ralph Howard Fowler obtained "Part II degree" from Cambridge. According to University of Cambridge[18], the two type of degree are part of the Tripos course taught in the faculty of mathematics in three or four years. Thus, we consider it is equivalent to the BSc degree of other participants. Édouard Herzen has no AIP page regarding his biography. In his descendant's interview[19], we can know that he studied chemistry and physics and later worked in the Solvay Institute in Belgium. However, there is no information about his education and the year he obtained the degree. The only information we found is that he published a thesis on Surface Tension in 1902, which we are not sure is a doctorate thesis.

Regarding the publication data, four participating physicists: Émile Henriot, Édouard Herzen, Paul Langevin and Jules-Émile Verschaffelt are missing. This can lead to data incomplete and unbalanced. Besides, the collected publications only contain the meta data, hence the content of them can not be analyzed. Consequently, some of the relationships described in the paper's content could not be located. For instance, in 1930, Auguste Piccard designed ships to explore the upper stratosphere to measure cosmic radiation; these vessels were intended to provide experimental evidence for Albert Einstein's theories [20]. However, this relationship is not supported by the available data. There is reason to believe that the network of relationships between these scientists is more interconnected than this project demonstrates.

The choice of the main subject in figure 4(a) was in certain cases difficult to make. Physicist like Einstein worked on so many subjects that it was a bit arbitrary to select one of them, but we chose the one where he had the greatest impact. Other choices could be seen as anachronisms, like the term *solid state physics* that only became a separate field in the 1940s [21]. Some physicists worked on this topic earlier but it is clear they worked in that field, even if it did not wear this name at that time.

6.2 Limitation on Methods

Although MCA helps to unreal the dominant subgroups in our dataset, the results produced by MCA are unfocused. Not all categories have the same weight in terms of scientific influence. Since we are analysing a relative small group of people in a specific domain, the results of MCA have a lot of overlaps.

The result of SNA does not display meaning and context itself. The edges in the networks are defined at the data collecting stage, which inevitable has missing information for historical data. Furthermore, the interpretation necessitates a closer examination of the source materials, such as the substance of the original publications or personal correspondences, which we were unable to accomplish due to the project's time constraints.

7 Conclusion & Future Work

The answer this project seems to indicate for the initial question *was the 1927 Solvay conference a turning point in history of modern physics ?* is no, at least from the perspective of the different criteria we looked at, like differences in key words in publications or number of publications between before and after the conference. Indeed, it has been observed that each physicist published the same order of magnitude of papers before and after the conference and the clouds of words for these two periods do not differ from each other. Moreover, according to network analysis, most of their relationships were formed before 1927, so this meeting did not have much impact on their cooperative relationship. The only turning point we observed was that the Fifth Solvay Conference was the first post-WWI Solvay conference that invited previously boycotted German and Austrian scientists.

In the end, the best learning that came out of this project is the questions that it raised for future work. The question about citation usages within paper has been sketched at section 5.3 in a small and partially arbitrary example of two papers, but the general question of citations and the roles they play nowadays and in the past, which seem really different from one another, could be much more deepened. Its interest could even be more emphasised by its dependency to the role of the conference. Indeed, the evolution of the role of this particular aspect of science is probably the most straightforward question that comes after this project. Who are conferences addressed to ? How is its public invited to it ? How did we arrived to our science popularisation conference of nowadays from very elitist and private conferences, and how are these later still organised in our days ? These two developments, on one side scientific papers and on the other scientific conferences, could both justify a single research question on their own, but must have shared some common changes in the mean time.

Before getting to the end, one should probably think again about what brought us here, in the footsteps of twenty-nine physicists. It was a photograph (fig.1). It was twenty-nine faces. It was, moreover, twenty-nine names, popular to the ears of anyone who was once interested in physics, but names that cannot be put as easily on the faces as they have been often heard. Probably because, these names became part of a certain myth. A myth that was built probably on the moment already, but also across the almost hundred years that passed since then. How was this myth built ? Do we and if yes, why do we need myths in science ? Many questions that could also be worth taking interest in them.

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