# Supplementary Information
# Predicting the Evolution of Physics Research from a complex network perspective

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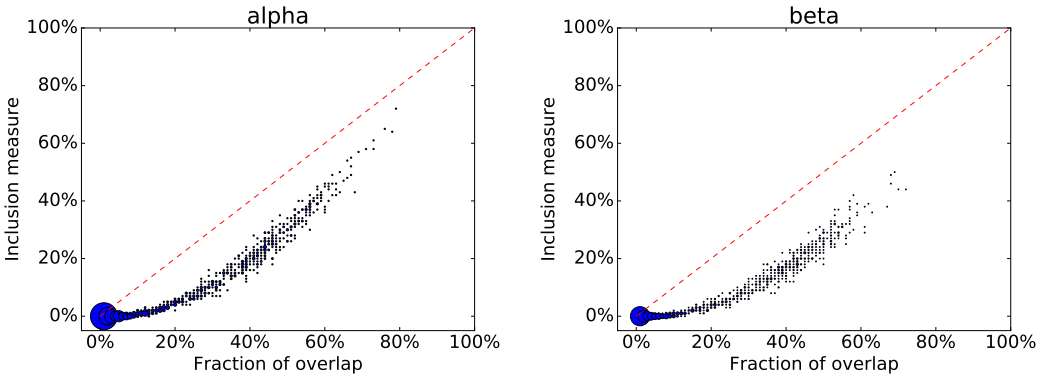
## The alpha and beta thresholds for event labelling

Two groups in the consecutive time windows are considered similar if at least one of their inclusion measures is greater than alpha or beta parameters. In other words, the alpha and beta parameters are thresholds which have to be satisfied to assign an event between two groups. The theoretical range of values for alpha and beta is between 0% and 100%. However, the most common values are selected from the range from 30% to 70%, depending on the density of the network and node's fluctuation year by year. In general, the selection of parameters should reflect the needs of researchers. For example, one may choose very high value (e.g. 80%) in order to preserve only very similar groups. In another case, it might be necessary to set very low value, e.g. 10% if the network is sparse or the fluctuation is high. In our study, we ran the GED method with alpha and beta parameters varying from 5% to 100%, to see how the number of events varies. Our goal was to have at least one event assigned to each TC. As the splitting and merging events involve several groups, we aimed to have on average slightly more than one event per TC. With this assumption, we selected 30% for both alpha and beta parameters in case of BCN, and 10% for alpha and beta parameters in case of CN. This values produced in total 479 events per 430 groups for BCN, and 492 events per 457 groups for CN.

## Correlation between overlap measure and inclusion measure

For BCN, we use the forward and backward intimacy indices to measure the closeness between TCs in consecutive time windows (years). For CN, we considered two types of measure: (i) a simple overlap measure of two groups (the relative fraction of common members), and (ii) an overlap of two groups enriched with the information about the importance of the common members. The latter is suggested by the GED method authors, who named their similarity measure the inclusion measure. One way to evaluate the importance of TC members is to use node centrality measures to rank them within the group. In our work, we are using the Social Position measure[1] (as suggested in the GED method), an idea based on the PageRank algorithm[2]. Saganowski *et al.*[3] found that using a richer similarity measure allows us to track group evolution more reliably. To better understand the difference between the simple overlap measure and the inclusion measure we compared values obtained with both measures in Fig. S1. It turned out that the inclusion measure is on average 20% lower than the simple overlap measure, and the corresponding values, i.e. 30% for the simple overlap and 10% for the inclusion measure, produce roughly the same number of the evolution events. However, the more complex version of the similarity measure (i.e. the inclusion measure), provided slightly better initial prediction results. Therefore, we finally utilized the inclusion measure in our calculations for CN.




(A) (B)

Figure S1: The scatter plots for simple overlap measure and inclusion measure for CNs between 1981 to 2010. The left panel (A) is for the alpha parameter, i.e. how the groups in $t$ are close to groups in $t+1$. The right panel (B) is for beta parameter, i.e. how the groups in $t+1$ are close to groups in $t$. The sizes of circles are proportional to the number of instances. The red dash lines are $y = x$ for reference only.

## Alluvial diagram for CN

Like the bibliographic coupling network (BCN), the co-citation network (CN) can also be visualized in the form of the alluvial diagram. The groups in a CN represent the papers from the past that are coherent and related to a certain topic that stimulates the present research lines.

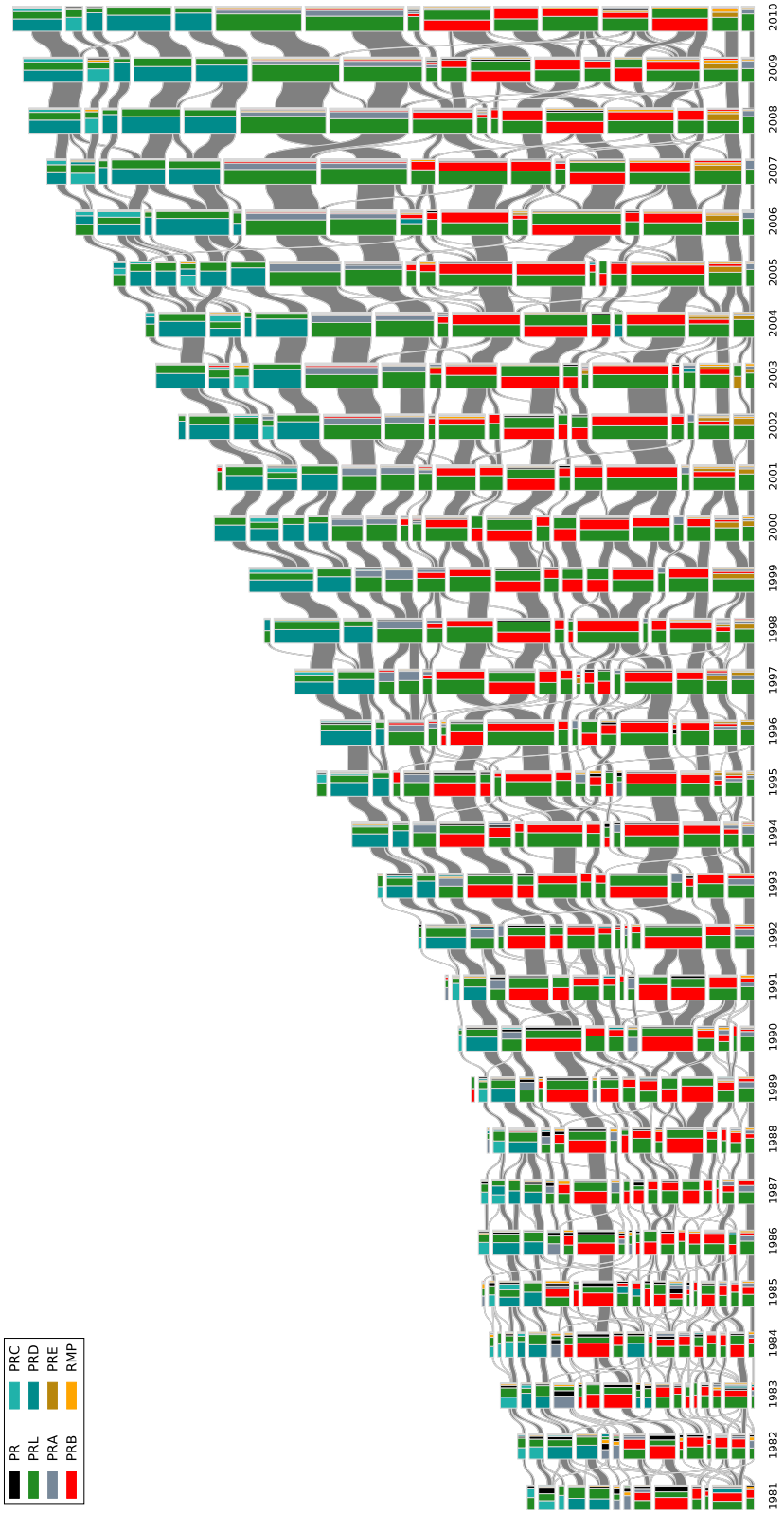



Figure S2: The alluvial diagram of APS papers' references (CNs) from 1981 to 2010. Each block in a column represents a TC extracted from the CN. The height of the block is proportional to the number of papers in the TC. For clarity, only TCs comprising more than 1% of all nodes in CNs are shown. TCs in successive years are connected by streams whose widths at the left and right ends are proportional to the relative overlap percentage. The colours inside a TC represent the relative contributions from different journals.

## The list of features used in the study

As we mentioned in **Future events prediction**, each observation contained 77 features (preselected from the initial 100). The full list of 100 features are showed in Tab. S1. Many features in this list are proposed for directed social network, therefore are inappropriate for our undirected BCN and CN. The symbol + indicates this feature was used in BCN prediction, while the symbol $*$ indicates this feature was used in CN prediction.

Table S1: List of all features used in the study. Features proposed in this study are shown in bold.

| Features group | Feature name | Feature description |
|---|---|---|
| Members/microscopic | sum_group_degree_in | The sum of indegree[4] of nodes belonging to the community calculated within the community. Indegree is a node measure defining the number of connections directed to the node |
| | avg_group_degree_in | The average value of indegree of nodes belonging to the community calculated within the community |
| | min_group_degree_in | The minimum value of indegree of nodes belonging to the community calculated within the community |
| | max_group_degree_in | The maximum value of indegree of nodes belonging to the community calculated within the community |
| | sum_group_degree_out | The sum of outdegree[4] of nodes belonging to the community calculated within the community. Outdegree is a node measure determining the number of connections outgoing from the node |
| | avg_group_degree_out | The average value of outdegree of nodes belonging to the community calculated within the community |
| | min_group_degree_out | The minimum value of outdegree of nodes belonging to the community calculated within the community |
| | max_group_degree_out | The maximum value of outdegree of nodes belonging to the community calculated within the community |
| | sum_group_degree_total+$*$ | The sum of total degree of nodes belonging to the community calculated within the community. Total degree is the sum of indegree and outdegree |
| | avg_group_degree_total+$*$ | The average value of total degree of nodes belonging to the community calculated within the community |
| | min_group_degree_total+$*$ | The minimum value of total degree of nodes belonging to the community calculated within the community |
| | max_group_degree_total+$*$ | The maximum value of total degree of nodes belonging to the community calculated within the community |

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**Table S1 – continued from previous page**

| Features group | Feature name | Feature description |
|---|---|---|
| | sum_group_betweenness+∗ | The sum of betweenness[4] of nodes belonging to the community calculated within the community. Betweenness is a node measure describing the number of the shortest paths from all nodes to all others that pass through that node |
| | avg_group_betweenness+∗ | The average value of betweenness of nodes belonging to the community calculated within the community |
| | min_group_betweenness+∗ | The minimum value of betweenness of nodes belonging to the community calculated within the community |
| | max_group_betweenness+∗ | The maximum value of betweenness of nodes belonging to the community calculated within the community |
| | sum_group_closeness+∗ | The sum of closeness[4] of nodes belonging to the community calculated within the community. Closeness is a node measure defined as the inverse of the farness, which in turn, is the sum of distances to all other nodes |
| | avg_group_closeness+∗ | The average value of closeness of nodes belonging to the community calculated within the community |
| | min_group_closeness+∗ | The minimum value of c of nodes belonging to the community calculated within the community |
| | max_group_closeness+∗ | The maximum value of closeness of nodes belonging to the community calculated within the community |
| | sum_group_eigenvector+∗ | The sum of eigenvector[5] of nodes belonging to the community calculated within the community. Eigenvector is a node measure indicating the influence of a node in the network |
| | avg_group_eigenvector+∗ | The average value of eigenvector of nodes belonging to the community calculated within the community |
| | min_group_eigenvector+∗ | The minimum value of eigenvector of nodes belonging to the community calculated within the community |
| | max_group_eigenvector+∗ | The maximum value of eigenvector of nodes belonging to the community calculated within the community |
| | avg_group_eccentricity+∗ | The average value of eccentricity[6] of nodes belonging to the community calculated within the community. Eccentricity of a node is its shortest path distance from the farthest other node in the graph |

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**Table S1 – continued from previous page**

| Features group | Feature name | Feature description |
|---|---|---|
| | min_group_eccentricity+∗ | The minimum value of eccentricity of nodes belonging to the community calculated within the community |
| | max_group_eccentricity+∗ | The maximum value of eccentricity of nodes belonging to the community calculated within the community |
| | sum_network_degree_in | The sum of indegree of nodes belonging to the community calculated within the network |
| | avg_network_degree_in | The average value of indegree of nodes belonging to the community calculated within the network |
| | min_network_degree_in | The minimum value of indegree of nodes belonging to the community calculated within the network |
| | max_network_degree_in | The maximum value of indegree of nodes belonging to the community calculated within the network |
| | sum_network_degree_out | The sum of outdegree of nodes belonging to the community calculated within the network |
| | avg_network_degree_out | The average value of outdegree of nodes belonging to the community calculated within the network |
| | min_network_degree_out | The minimum value of outdegree of nodes belonging to the community calculated within the network |
| | max_network_degree_out | The maximum value of outdegree of nodes belonging to the community calculated within the network |
| | sum_network_degree_total+∗ | The sum of total degree of nodes belonging to the community calculated within the network |
| | avg_network_degree_total+∗ | The average value of total degree of nodes belonging to the community calculated within the network |
| | min_network_degree_total+∗ | The minimum value of total degree of nodes belonging to the community calculated within the network |
| | max_network_degree_total+∗ | The maximum value of total degree of nodes belonging to the community calculated within the network |
| | sum_network_betweenness +∗ | The sum of betweenness of nodes belonging to the community calculated within the network |
| | avg_network_betweenness+∗ | The average value of betweenness of nodes belonging to the community calculated within the network |

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**Table S1 – continued from previous page**

| Features group | Feature name | Feature description |
|---|---|---|
| | min_network_betweenness+∗ | The minimum value of betweenness of nodes belonging to the community calculated within the network |
| | max_network_betweenness+∗ | The maximum value of betweenness of nodes belonging to the community calculated within the network |
| | sum_network_closeness+∗ | The sum of closeness of nodes belonging to the community calculated within the network |
| | avg_network_closeness+∗ | The average value of closeness of nodes belonging to the community calculated within the network |
| | min_network_closeness+∗ | The minimum value of closeness of nodes belonging to the community calculated within the network |
| | max_network_closeness+∗ | The maximum value of closeness of nodes belonging to the community calculated within the network |
| | sum_network_eigenvector+∗ | The sum of eigenvector of nodes belonging to the community calculated within the network |
| | avg_network_eigenvector+∗ | The average value of eigenvector of nodes belonging to the community calculated within the network |
| | min_network_eigenvector+∗ | The minimum value of eigenvector of nodes belonging to the community calculated within the network |
| | max_network_eigenvector+∗ | The maximum value of eigenvector of nodes belonging to the community calculated within the network |
| | avg_group_coefficient[7]+∗ | The average of the local clustering coefficients of all the nodes in the community |
| | avg_network_coefficient[7]+∗ | The average of the local clustering coefficients of all the nodes in the network |
| Group/mesoscopic | group_size+∗ | The number of nodes in the group |
| | group_density[7]+∗ | The number of connections between nodes in the group in relation to all possible connections between them |
| | group_cohesion[8]+∗ | The vertex connectivity of the community |
| | group_coefficient_global[7]+∗ | The ratio of the triangles and the connected triples in the community |
| | group_reciprocity[9] | A fraction of edges that are reciprocated within the community |
| | group_leadership[4]+∗ | A measure describing centralization in the community (the largest value is for a star network) |

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**Table S1 – continued from previous page**

| Features group | Feature name | Feature description |
|---|---|---|
| | neighborhood_out | The number of nodes outside the community that have incoming connection from the nodes inside the community divided by the number of nodes in the community |
| | neighborhood_in | The number of nodes outside the community that have outgoing connection to the nodes inside the community divided by the number of nodes in the community |
| | neighborhood_all+∗ | The number of nodes outside the community that are connected to the nodes inside the community divided by the number of nodes in the community |
| | group_adhesion[8]+∗ | The minimum number of edges needed to be removed to obtain a community which is not strongly connected |
| | alpha[10] | The GED inclusion measure of group $G_i$ from time window $T_n$ in group $G_j$ from $T_{n+1}$ |
| | beta[10] | The GED inclusion measure of group $G_j$ from time window $T_{n+1}$ in group $G_i$ from $T_n$ |
| | network_ratio_size+∗ | The ratio of *group_size* to *network_size* |
| | network_ratio_density+∗ | The ratio of *group_density* to *network_density* |
| | network_ratio_cohesion+∗ | The ratio of *group_cohesion* to *network_cohesion* |
| | network_ratio_coefficient_global+∗ | The ratio of *group_coefficient_global* to *network_coefficient_global* |
| | network_ratio_coefficient_average+∗ | The ratio of *group_clustering_coefficient* to *network_clustering_coefficient* |
| | network_ratio_reciprocity | The ratio of *group_reciprocity* to *network_reciprocity* |
| | network_ratio_leadership+∗ | The ratio of *group_leadership* to *network_leadership* |
| | network_ratio_eccentricity+∗ | The ratio of *avg_group_eccentricity* to *network_avg_eccentricity* |
| | network_ratio_adhesion+∗ | The ratio of *group_adhesion* to *network_adhesion* |
| | **phys_rev∗** | **The number of articles belonging to the group that were published in the Physical Review journal** |
| | **phys_rev_a+∗** | **The number of articles belonging to the group that were published in the Physical Review A journal** |
| | **phys_rev_b+∗** | **The number of articles belonging to the group that were published in the Physical Review B journal** |
| | **phys_rev_c+∗** | **The number of articles belonging to the group that were published in the Physical Review C journal** |

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| Features group | Feature name | Feature description |
|---|---|---|
| | **phys_rev_d+∗** | **The number of articles belonging to the group that were published in the Physical Review D journal** |
| | **phys_rev_e+∗** | **The number of articles belonging to the group that were published in the Physical Review E journal** |
| | **phys_rev_lett+∗** | **The number of articles belonging to the group that were published in the Physical Review Letters journal** |
| | **phys_rev_stab+∗** | **The number of articles belonging to the group that were published in the Physical Review STAB journal** |
| | **phys_rev_stper+** | **The number of articles belonging to the group that were published in the Physical Review STPER journal** |
| | **physics∗** | **The number of articles belonging to the group that were published in the Physics journal** |
| | **rev_mod_phys+∗** | **The number of articles belonging to the group that were published in the Review of Modern Physics journal** |
| | **sum_group_age+∗** | **The sum of age of articles belonging to the group. In the co-reference network the age of an article is the average age of the articles it references to. In the co-citation network the age of an article is the age of the articles being cited.** |
| | **avg_group_age+∗** | **The average age of articles belonging to the group** |
| | **min_group_age+∗** | **The minimum age of articles belonging to the group** |
| | **max_group_age+∗** | **The maximum age of articles belonging to the group** |
| | **network_ratio_avg_group_age+∗** | **The ratio of avg_group_age to the average age of all articles in the network** |
| | time_window+∗ | The number of time window from which the community instance was obtained |
| Network/macroscopic | network_size+∗ | The number of nodes in the network |
| | network_density+∗ | The number of connections between nodes in the network in relation to all possible connections between them |
| | network_cohesion+∗ | The vertex connectivity of the network |
| | network_coefficient_global+∗ | The ratio of the triangles and the connected triples in the network |
| | network_coefficient_average+∗ | The average of the local clustering coefficients of all the nodes in the network |

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**Table S1 – continued from previous page**

| Features group | Feature name | Feature description |
|---|---|---|
| | network_reciprocity | A fraction of edges that are reciprocated within the network |
| | network_leadership+∗ | A measure describing centralization in the network (the largest value is for a star network) |
| | network_avg_eccentricity+∗ | The average value of eccentricity of nodes within the network. |
| | network_adhesion+∗ | The minimum number of edges needed to be removed to obtain a graph which is not strongly connected |

# The visualization of TC

In Fig. S3 we show the topic clusters for BCN in 1991. By checking top cited papers in each TC, we found the red TC (top) is mainly about *ab initio* calculation; the orange TC (top right) is mainly about high temperature superconductor; the dark blue TC is mainly about quantum dot and quantum well; the black TC is mainly about excitonic effect in quantum well; the green TC is mainly about electromagnetic related optics; the light blue TC is mainly about surface physics and statistical physics; the purple TC is mainly about cosmology; the yellow TC is mainly about particle physics. The above descriptions are not rigorous measurements, but subjective impressions based on author's knowledge about physics. The intention is to give readers a sensing of TC space rather than a quantitative study.

# References


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[8] White, D. R. & Harary, F. The Cohesiveness of Blocks In Social Networks: Node Connectivity and Conditional Density. *Sociological Methodology* **31**, 305–359 (2001). DOI 10.1111/0081-1750.00098.

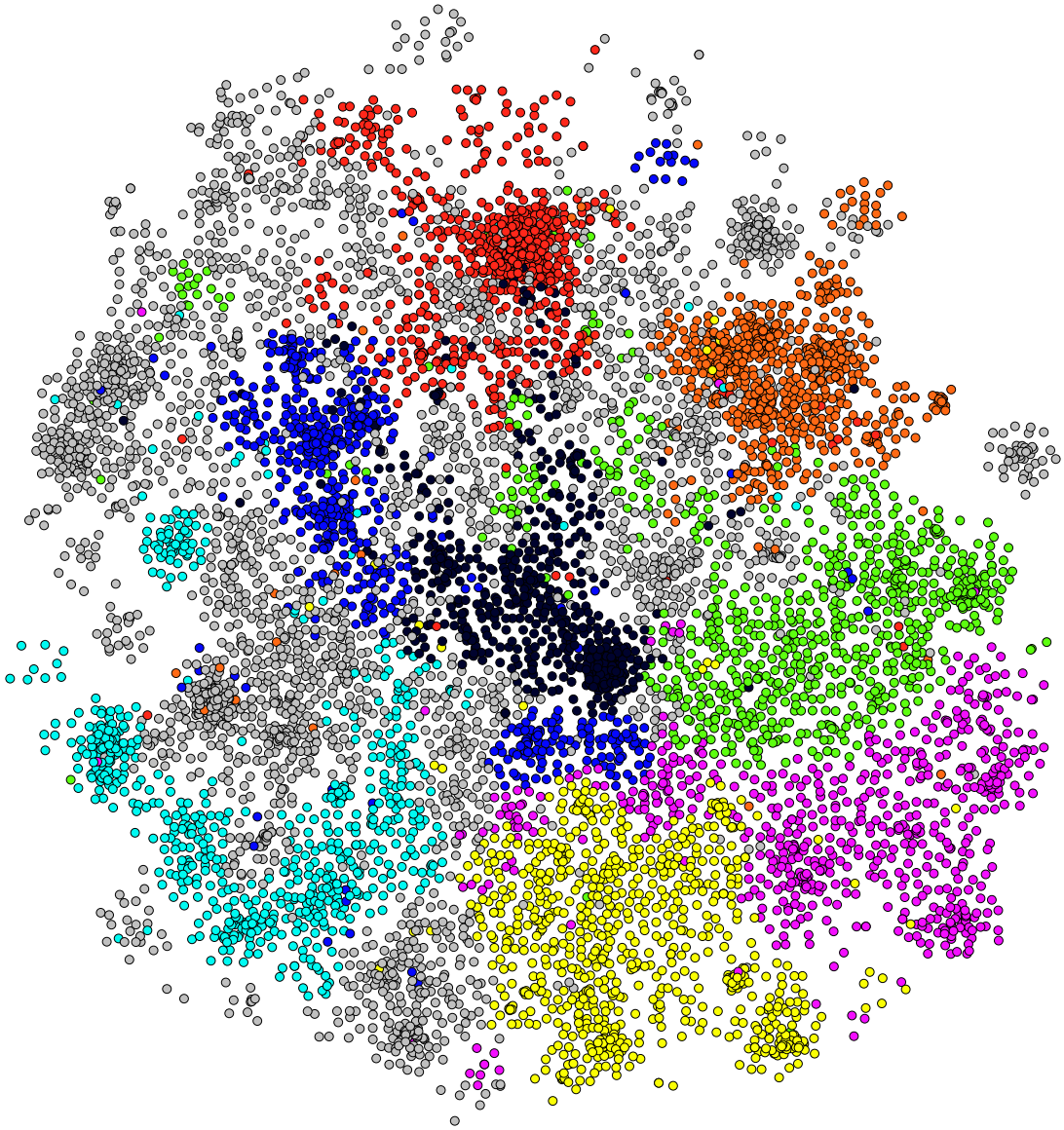

Figure S3: Bibliographic coupling network in 1991. Each node represents a paper. Papers in the same community (detected by Louvain method) are given the same color for eight largest communities, papers in other smaller communities are grey. The layout algorithm be used is "OpenOrd" in Gephi.

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[10] Bródka, P., Saganowski, S. & Kazienko, P. GED: the method for group evolution discovery in social networks. *Social Network Analysis and Mining* **3**, 1–14 (2013). DOI 10.1007/s13278-012-0058-8.