A proposal for a quantitative indicator of original research output

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The need to assess scientific productivity has always been present in the history of science, and it plays an ever growing role considering the budgetary constraints that have emerged since almost three decades of post-cold-war science. A single-number indicator of scientific impact, named $h$-index, was proposed more than a decade ago, and since then has been progressively considered as relevant especially for hiring, tenure, and promotion processes in many academic systems [1]. In spite of the caveats explicitly discussed in detail by his originator, the $h$-index is currently considered the most crucial indicator for science output, and is affecting significantly the evolution of entire research fields. There is an extensive literature on the shortcomings of the $h$-index and of the fact that it represents, in an average sense, an indicator derivable from the total number of citations. We first discuss some of the drawbacks of the broadly adopted $h$-index and of the arguments on how different indicators may shape the future of science are finally discussed. Qualitative impact of an individual or an institution. The $h$-index is contracting the full information of a histogram in which the number of citations of each paper is plotted versus the progressive number of paper in decreasing order of citations, the “citation curve” $y = N_{\text{cit}}(i)$, and is obtained by intersecting this histogram with the line $z = i$ [1].

A number of criticisms has been raised against the capability of the $h$-index to adequately represent scientific accomplishments, some of them already discussed at its very inception. While the complete information on the scientific output is available through the citation curve, the $h$-index is a coarse-grained indicator which does not provide information neither on the papers with high number of citations, nor on the tail consisting of papers with low number of citations: By construction, all the relevant information of the $h$-index is guaranteed [5].

Therefore, the $h$-index penalizes researchers switching to different fields with respect to the ones continually pursuing the same problem and presumably citing their former contributions in the same field. This issue could be easily corrected in the analysis of most databases for which self-citations are available, although this has not been systematically implemented so far. There are other issues, however, that cannot be easily addressed with the $h$-index. The size of the relevant scientific community is indeed very crucial, so problems interesting few researchers, no matter how potentially relevant and challenging they might be, are downplayed with respect to mainstream research involving larger numbers of researchers and papers. Since, typically, the size of scientific communities increases in time, researchers who built up a productive career several decades ago are somewhat penalized with respect to the newer generations. Of course, an indicator which depends on the size of the community and on

**I. INTRODUCTION**

The use of quantitative indicators of scientific productivity seems now quite widespread for assessing researchers and research institutions. There is a general perception, however, that these indicators are not necessarily representative of the originality of the research carried out, being primarily indicative of a more or less prolific scientific activity and of the size of the targeted scientific subcommunity. We first discuss some of the drawbacks of the broadly adopted $h$-index and of the secondary indicator, merely representing a number related to the total number of citations. Moreover, we show that apparently paradoxical features emerge by considering deviations from the average $h$-index. We then introduce an index more related than the $h$-index to the degree of originality of scientific research and the perception that we have of outstanding scientists, providing two examples from last century physics. While we warn for the general danger of adopting single-number indicators as the main parameter for decision-making in science policy, we finally argue that adoption of the proposed $\Omega$-index may result in a quite different historical evolution of various research fields with respect to the one determined by the $h$-index.

**II. THE $h$-INDEX AS A SECONDARY INDICATOR**

The $h$-index, the integer number for which $h$ papers have collected at least $h$ citations, is considered a simple, effective way to quantify with a single number the
time can hardly be suitable to compare different fields or researchers with different seniority and interests, and alternative measures have been discussed to overcome this strong limitation [6].

We now show that there is a strong correlation between the total number of citations \( N_{\text{cit}} \) and the \( h \)-index. An empirical relation was already identified in [7], as \( N_{\text{cit}} = a h^2 \), with \( a \) a parameter in the 3-5 range. We would like to derive from first principles a relationship between \( N_{\text{cit}} \) and the expected \( h \)-index. In order to reach this goal, it is worth to stress that, for a given total number of citations \( N_{\text{cit}} \), various \( h \)-indexes may be achieved. In one extreme case, it is possible to have a histogram in which one paper gets all \( N_{\text{cit}} \) and all others get zero citations. Next to this, it is possible that two papers are instead cited, and all the other are not, for instance one with \( N_{\text{cit}} - 1 \) citations, the other with one citation.

In general, the number of possible distinct configurations given a number of citations coincides with the evaluation of the partitions of \( N_{\text{cit}} \). This number increases quickly with \( N_{\text{cit}} \) exponentially according to the asymptotic estimate of Hardy, Ramanujan and Uspensky – for instance for \( N_{\text{cit}} = 100 \) there are 190,569,292 partitions, while for \( N_{\text{cit}} = 1000 \) there are \( \approx 2.40615 \times 10^{313} \) partitions. Each partition has an associated \( h \)-index, and one could obtain an average \( h \)-index by averaging the \( h \)-indexes over all the partitions, for instance assuming that each has the same probability to occur \( a \) priori. This becomes intractable for the typical values of available \( N_{\text{cit}} \), and therefore we adopt an approximation consisting in limiting the number of configuration to “rectangular” patterns in which \( k \) papers share the same number of citations, \( \sqrt{N_{\text{cit}}} \), at least under the two hypotheses made, \( i.e. \) the “rectangular” one and the fact that

\[
\langle h \rangle = \frac{1 + 2 + \ldots \text{int}(\sqrt{N_{\text{cit}}})}{\text{int}(\sqrt{N_{\text{cit}}})} = 1 + \frac{\text{int}(\sqrt{N_{\text{cit}}})}{2} \approx \frac{1}{2} \sqrt{N_{\text{cit}}},
\]

with the last expression holding for \( N_{\text{cit}} \gg 1 \). Therefore, the average \( h \)-index, \( \langle h \rangle \), at least under the two hypotheses made, \( i.e. \) the “rectangular” one and the fact that
$N_{\text{cit}} = N_p$, is nothing but a reparametrization of the total number of citations, just differing from it in being sensitive to the details of the citation curve at the crossover point. The empirical factor $a$ introduced in [1] is recovered, at its central value of 4, in our rectangular approximation. Figure 2 show an example suggesting that $\langle h \rangle$ evaluated as in Eq. [1] is a good interpolation of real data, evaluated from the personal experience for a variety of researchers of different seniority, all sharing average achievements, and for a broad range of total citations, ranging from postgraduate students who left academic research immediately after their studies to a Nobel laureate.

Interesting considerations may be made by looking at deviations of the actual data from $\langle h \rangle$, which may be related to the variability of the $a$ parameter noticed in [1]. For the same total number of citations, researchers with an actual $h$-index significantly smaller than the corresponding $\langle h \rangle$ have few papers with high number of citations, and many papers with marginal impact, with the extreme case of all citations available in a single paper. At the opposite end of the spectrum lies instead a class of researchers with several medium-impact papers, but no papers with large numbers of citations, with $\sqrt{N_{\text{cit}}}$ papers each having $\sqrt{N_{\text{cit}}}$, and all others with zero citations. The typical presence of more citations than papers, especially for more senior researchers, breaks the symmetry of configurations on which Eq. [1] is derived, weighting more the lower configurations with large number of citations. This corresponds to the case of a closer to smaller values than the middle value of 4 in the empirical remark reported in [1].

The case of researchers having $h \ll \langle h \rangle$ represents individuals pursuing high-risk/high-reward work, while the opposite case is more representative of researchers who, in Kuhn’s approach, are more inclined to work on normal science. In the perception of the scientific community and the outside world, a successful scientist is typically more associated to the former case [2] [8]. By looking at history of physics, it turns out that most of the founding fathers of quantum mechanics have in fact $h$-indexes well below the corresponding average one. In more recent times, there is the striking case of Nobel laureate Peter Higgs who, according to the Web of Science, has a $h = 11$ with 22 papers totaling 5642 citations as of 10/17/2017. Meanwhile there are various researchers who have $h$-index in the 80-100 range and who, although well-known in their community, are not necessarily perceived as belonging to the same category of creative thinkers as Higgs. They are rather considered as belonging to a category of prolific scientists, may be also due to the large size of their research groups or the sheer size of the community to which they belong. A question arises naturally: As the $h$-index seems to be anticorrelated with breakthrough results and original work, is it possible to find another indicator overcoming this limitation? While a rather sophisticated indicator has been already proposed [9], in the next section we will try to give a simpler answer to this question.

III. AN INDICATOR SUITED FOR SCIENTIFIC ORIGINALITY

The assessment of creative work is not univocal, and creativity is very often rather elusive and intangible, see for instance artist communities in which the consensus on creativity is often controversial, with the debate sustaining an entire sector, those of the critics, for centuries. Late assessments, while crucial in history and sociology of science, are manifestly of marginal interest for academic comparison of candidates. However, if one insists in aiming to quantify originality with a single number, a simple indicator may be constructed as follows. We introduce the originality index $\Omega$ as the ratio

$$\Omega = \frac{N_{\text{cit}} - N_{\text{ref}}}{N_{\text{ref}}}$$

where $N_{\text{cit}}$, as before, is the total number of citations of all the papers of a given individual or institution, and $N_{\text{ref}}$ is the total number of references cited in the same papers. Qualitatively, one may imagine that any scientific result emerges from previous knowledge, here quantified by the amount of references cited in each contribution. The success, in terms of originality, of the new result will be measured by the ability to create new scholarship, measured in turn by the citations obtained with respect to the existing scholarship. In the example of Peter Higgs, the apparently modest $h$-index of 11 is contrasted by an $\Omega=21.04$, thanks to a total of only 256 references in his papers.

There are various advantages of this indicator. As the $h$-index, it is simple to evaluate. The total number of citations is already available in various databases, and it needs to be complemented by a count on the total number of references. The latter does not need to be updated until a new published paper is added to the database. If the average number of citations per paper $n_{\text{cit}}$ and the average number of references per paper $n_{\text{ref}}$ are available, the originality index is simply expressed in terms of these intensive parameters as $\Omega = n_{\text{cit}}/n_{\text{ref}} - 1$. Self-citations are automatically canceled out as, by definition, they contribute to both quantities in the numerator of Eq. [2]. The production of papers of secondary relevance will be inhibited if one seeks to maximize $\Omega$, as they will most likely end up in adding many more references than future citations. Likewise, the proliferation of secondary scholarship with a priori little originality (e.g. review articles), will also affect negatively the originality index at least as long as the intrinsically large number of references will not be offset by a proportionate number of citations.

The $\Omega$-index is also robust with respect to another possible phenomenon, authorship fusion, which instead may be favorable, barring obvious ethical principles, having in
TABLE I: Rankings of the participants to the fifth Solvay Conference on Physics in 1927 according to data available on Web of Science. Names of the participants in alphabetic order, number of published papers through their whole career $N_p$, total number of citations $N_{cit}$, total number of cited papers $N_{ref}$, $h$-index, average $h$-index, and $\Omega$-index are reported.

| Author | $N_p$ | $N_{cit}$ | $N_{ref}$ | $h$ | $(\langle h \rangle)$ | $\Omega$ |
|--------|-------|-----------|-----------|-----|----------------------|--------|
| Bohr,N. | 79   | 6535      | 730       | 29  | 41.3                 | 8.36   |
| Born.M. | 192  | 11474     | 1380      | 42  | 60.1                 | 13.3   |
| Bragg,W.L. | 98  | 4105      | 643       | 37  | 32.0                 | 5.38   |
| Brillouin,L. | 74  | 2298      | 591       | 20  | 24.0                 | 2.89   |
| Compton,A.H. | 110 | 2157      | 1163      | 23  | 23.2                 | 0.86   |
| Curie,M. | 25   | 145       | 502       | 5   | 6.0                  | -0.71  |
| de Broglie,L. | 120 | 1229      | 374       | 14  | 17.5                 | 2.29   |
| de Donder,T. | 29  | 33        | 86        | 3   | 2.9                  | -0.62  |
| Debye,P. | 153  | 18800     | 1198      | 52  | 88.6                 | 14.69  |
| Dirac,P.A.M. | 98  | 21536     | 320       | 46  | 73.3                 | 66.22  |
| Ehrenfest,F. | 60  | 1355      | 610       | 18  | 18.4                 | 1.22   |
| Einstein,A. | 129 | 30171     | 186       | 53  | 86.8                 | 161.21 |
| Guye,C.E. | 22   | 10        | 17        | 2   | 1.6                  | -0.41  |
| Heisenberg,W. | 113 | 9790      | 1346      | 41  | 49.5                 | 6.27   |
| Henriot,E. | 12   | 73        | 68        | 4   | 4.3                  | 0.07   |
| Herzen,E. | 1    | 1         | 1         | 1   | 0.5                  | 0.90   |
| Knudsen,M. | 23   | 1614      | 104       | 14  | 20.1                 | 14.52  |
| Kramers,H.A. | 61  | 12958     | 653       | 36  | 56.9                 | 18.84  |
| Langevin,P. | 29   | 2393      | 184       | 11  | 24.5                 | 12.01  |
| Langmuir,I. | 154 | 30138     | 1994      | 58  | 86.8                 | 14.11  |
| Lorentz,H.A. | 46  | 434       | 133       | 8   | 10.4                 | 2.26   |
| Pauli,W. | 41   | 4233      | 443       | 27  | 32.5                 | 8.56   |
| Piccard,A. | 25   | 105       | 71        | 6   | 5.1                  | 0.48   |
| Planck,M. | 90   | 1388      | 454       | 13  | 18.6                 | 2.96   |
| Richardson,O.W. | 146 | 693       | 1311      | 12  | 13.2                 | -0.39  |
| Schrödinger,E. | 86  | 8844      | 853       | 29  | 47.0                 | 0.37   |
| Verschaffelt,J.E. | 33  | 25        | 220       | 3   | 2.5                  | -0.89  |
| Wilson,C.T.R. | 34  | 1296      | 119       | 16  | 18                   | 9.89   |

mind maximization of the $h$-index. Suppose that there are two disjoint groups of authors $A$ and $B$ for two papers, their $h$-index can be increased if the authors agree to share authorship, as this will allow to collect more citations on the common paper. This gregarious author clustering is, instead, mitigated if the $\Omega$ index is to be maximized, because the presence of a distinct set of references $N_{ref}^A$ and $N_{ref}^B$ will make the fusion less advantageous, unless of course the two sets will coincide, in which case it may indicate that actually the two groups of authors have at least genuinely common research interests. The fusion phenomenon is particularly striking for researchers who suddenly switch from a few-collaborator production mode to become members of a large, inclusive collaboration. It is easy to observe that researchers who opted to join a large research collaboration, as it happens for instance in astronomy and high-energy physics, experience a sudden increase in the number of citations and the related $h$-index, with respect to people persisting with a small-science mode of production.

Maximization of the $\Omega$-index is primarily obtained by switching to new problems, instead of staying on the same territory for a long time which will maximize the $h$-index as discussed above. Perhaps one of the most iconic example of this optimization is provided by Enrico Fermi, who has $h=41$ with 82 papers, $N_{cit}=10,904$, and $N_{ref}=515$, corresponding to $\Omega=20.17$. Most notably, Fermi has 17 papers containing no references, among these the first report on “Radioactivity induced by neutron bombardment” (cited 75 times), and the paper introducing a model for weak interactions with 10 references and 648 citations (with no other follow-up paper written on the same subject). While the $h$-index of Fermi does not seem particularly impressive today, the large $\Omega$-index speaks a lot about his agility to give original and impactful contributions in a broad range of subfields of physics.

To better quantify the difference in the two indicators, we have taken the participants of the fifth Solvay Conference on Physics in 1927, and compared their $h$ and $\Omega$ indexes, in Table I. The analysis is then refined in Fig. [3] where we plot the $\Omega$-index versus the deviation of the actual $h$-index from its average value as defined in Eq. [1]. It is evident that well-renowned physicists have an $h$-index far smaller than the average one, and $\Omega$ indexes typically larger than unity. The striking figure of the $\Omega$-index for the most famous physicist of the last century, Albert Einstein, is manifest.

The analysis has been also repeated for another relevant period around the mid of the last century. In Table II we report the relevant quantities for the Nobel laureates in the 1955-1965 period. This period has been chosen for a variety of reasons. First, it is one in which there have been enormous breakthroughs, including new technologies and devices such as lasers, nuclear magnetic resonance, transistors and personal computers, particle detectors and accelerators, artificial satellites, fission nuclear power plants and tokamaks, on which we are still working. Second, on the theory side, this decade starts with the recognition of a puzzle in the high-precision spectroscopy of hydrogen, the Lamb-shift, and ends with recognition of the theory capable of justifying it, renormalized quantum electrodynamics; the latter, after fifty years, is still the paradigm against which to confront any
other quantum field theory. An explosion of discoveries and inventions deserves an analysis in itself, especially in comparison to the relative stagnation of today’s research. It seems evident that a variety of factors, including massive public funding of basic science, expansion of educational opportunities, and the fallout of the research and development carried out during WWII, played a major role in this exceptional period. Third, this allows us for testing the robustness of the available databases as in the period analyzed in Table I there can be missing papers, citations and references due to lack of archival data for that early period, in which science results were also communicated with different channels than the publication in scientific journals. In Fig. 3 we repeat the same analysis as in Fig. 2, confirming the trend of lower h-indexes than the ones expected on average.

The Ω-index may even be used to compare with some degree of credibility different fields of science, or different subfields, without the introduction of rescaling factors. Although this needs to be checked with detailed analyses, a plausibility argument in favor of this point is given by considering two extreme cases based on hypothetical (yet typical) common-sense figures: the one of a mathematician achieving 60 citations in 10 papers in which there are a total of 20 references, and the case of an experimental high-energy physicist who collects 30,000 citations coauthoring a total of 200 papers, each with 50 references. They will both correspond to an h-index of 50, and yet one of a mathematician achieving 60 citations in 10 papers, and the other a high-energy physicist who collects 30,000 citations coauthoring a total of 200 papers, each with 50 references. This seems to be what common sense suggests as a series of breakthroughs.

While the h-index is monotonic in time, the Ω-index is not, and prolific production of incremental papers following a breakthrough, or of secondary scholarship like review papers, will tend to decrease the Ω-index. At the same time, the h-index is bounded to the total number of published papers after a researcher ceases the scientific activity, while the Ω-index can grow indefinitely. In an apparent paradoxical fashion, as an alternative to produce other breakthrough papers, the best strategy to maintain or increase a large Ω-index is to stop publishing for a while, just focusing on the problem at hand or studying to tackle a completely new problem. This seems to be what common sense suggest to secure a series of breakthroughs, high-risk/high-reward, results.

The main drawback of the Ω-index seems to be the risk that some authors will tend to minimize as much as possible references to previous work, which will require a more focused action from the side of referees and

| Author | $N_L$ | $N_{SR}$ | $N_{Ref}$ | $\langle h \rangle$ | $\Omega$ |
|--------|-------|----------|-----------|----------------|--------|
| Lamb, W.E. | 123 | 9356 | 375 | 48.4 | 3.14 |
| Kusch, P. | 86 | 3809 | 916 | 27.8 | 3.16 |
| Hardey, J. | 151 | 24696 | 2221 | 24.5 | 10.12 |
| Brattain, W.H. | 58 | 2950 | 619 | 24.7 | 3.77 |
| Shockley, W.B. | 127 | 25209 | 1502 | 57.9 | 15.78 |
| Lee, T.D. | 190 | 22920 | 3157 | 70.7 | 6.26 |
| Yang, C.N. | 184 | 25803 | 2108 | 55.0 | 11.24 |
| Cherenkov, P.A. | 25 | 83 | 428 | 5 | 0.81 |
| Frank, I. | 54 | 329 | 775 | 10 | 0.58 |
| Tamm, I.E. | 17 | 95 | 161 | 5 | 0.41 |
| Segré, E. | 93 | 2752 | 1390 | 29 | 0.98 |
| Chamberlain, O. | 121 | 2801 | 1616 | 31 | 0.73 |
| Glaser, D.A. | 66 | 1577 | 924 | 22 | 0.91 |
| Hofstadter, R. | 223 | 9264 | 3751 | 49 | 1.47 |
| Mossbauer, R.L. | 92 | 3504 | 1958 | 28 | 0.79 |
| Landau, L.D. | 74 | 11810 | 354 | 38 | 0.32 |
| Wigner, E.P. | 151 | 16503 | 1934 | 45 | 0.64 |
| Goeppert-Mayer, M. | 10 | 843 | 89 | 7 | 0.84 |
| Jensen, J.H.D. | 28 | 1225 | 401 | 12 | 1.75 |
| Basov, N.G. | 532 | 5637 | 7193 | 36 | 8.22 |
| Prokhorov, A.M. | 1245 | 10572 | 13608 | 41 | 0.41 |
| Townes, C.H. | 340 | 19295 | 7345 | 63 | 0.63 |
| Feynman, R.P. | 77 | 26848 | 793 | 39 | 0.93 |
| Schwinger, J. | 191 | 28693 | 1334 | 73 | 0.47 |
| Tomonaga, S.-I. | 31 | 1978 | 221 | 14 | 0.22 |

TABLE II: Rankings of the Nobel laureates in Physics in the 1955-1965 period.

FIG. 4: Plot of the Ω-index vs. the deviation of the h-index from its average value for the Nobel laureates in the 1955-1965 timeframe, with highlights of physicists having the largest Ω-index.
IV. CONCLUSIONS

We have discussed two relevant drawbacks of the $h$-index if used to identify originality in scientific work. First, in an average sense its value is merely determined once the number of citations is known. Second, deviations from such an average value indicate that lower values of the $h$-index correspond to a small set of highly cited papers, while higher values are indicative of cumulative, medium-impact science. We have then introduced a simple indicator, the $\Omega$-index, which appears to better approximate the perceived feeling of a contribution being more or less original. This is corroborated by the analysis of data available on two historical periods in which highly creative work in Physics has been performed, one corresponding to the birth of the “new” quantum mechanics, the other to the enormous number of breakthroughs experienced in the Fifties. The analysis of the two samples shows that, by adopting the $\Omega$-index as the unique indicator for hiring and promotion, as could happen these days, most of the prominent scientist in the lists would have not been considered for academic positions even with post-mortem applications. The dynamics of optimization of the $\Omega$-index involves more feedback and nonlinearity, and does not end up encouraging unlimited proliferation of papers and review articles.

Finally, we would like to briefly comment on how the evolution of science may be affected by the active use of different indicators. A community aiming to maximize the $h$-index will try to be as prolific as possible in terms of papers and review articles, favoring authorship fusion processes, large collaborations, and discouraging changes of subfields. Demonstrational physics, in which a well-established theory is repeatedly confirmed in the laboratory for technological purposes, and applied sciences at large, may tend to benefit more from the $h$-index. Conversely, a community willing to maximize the $\Omega$-index will carefully consider the need to publish new papers, and to cite former papers, will favor the opening of uncharted territories for which former references may be scarce or barely existing, will discourage review papers unless they fill a clearly perceived gap, and will mitigate the incentive for authorship fusion. More theoretically-oriented work, especially in basic mathematics and surrounding fields, and pioneering experimental work in fields for which the theoretical counterpart is not settled or not even existing, could greatly benefit from the adoption of the $\Omega$-index. At a strictly individual level, leadership is more recognized with the $h$-index, while pioneering capabilities are more recognized with the $\Omega$-index. This suggests that the $\Omega$-index should be considered as an alternative, or at least complementary, to the $h$-index, in all subfields of basic/long-term return science, since a blind, pedantic application of the $h$-index alone could result in devastating effects on the entire scientific ecosystem.

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