Two new discipline-independent indices to quantify individual's scientific research output

2007 J. Phys.: Conf. Ser. 90 012018

(http://iopscience.iop.org/1742-6596/90/1/012018)

Two new discipline-independent indices to quantify individual's scientific research output

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Abstract. Interest in quantitative measurement of scientific output has been steadily growing because of increasing needs in the evaluation of candidates for new positions and promotions in academic careers. Recently, a new index H was proposed; it is based on an hyperbolic relationship between the number of citations and the number of papers of a given investigator, which intersects with the equality straight line. The crossing point gives the number of papers that received at least H references in a predetermined period of time. Such index neglects the contribution of the less cited papers and depends strongly on the discipline. Herein, using Hirsch's crossing point idea, we propose two new normalized indices, selectivity S and amplitude A, that are independent on the discipline and that take into account the whole spectrum of published and cited papers. The proposed method was applied to 100 scientists using information obtained from SCOPUS. The potential function appeared as the best fit to the data. Correlation coefficients were always high ($r = 0.79 \pm 0.11$). Most of the authors displayed a marked selectivity because a typical researcher concentrates only on a single subject or perhaps a few while a wide reach did not predominate. In conclusion, these parameters are proposed as a way to complement the scientific evaluation process of a candidate.

1. Introduction

Ever since Eugene Garfield, in 1955, from the Institute for Scientific Information (ISI), Philadelphia, introduced the concept of impact factor (IF) [1], interest in quantitative measure of scientific output has been steadily growing. Among other reasons, this interest results from increasing needs for improved methodologies to be used in the evaluation of candidates for new positions and promotions in scientific and academic careers.

Recently, Hirsch, in 2005, proposed a new index based on certain acceptable assumptions, which led to a shifted hyperbolic relationship between the number of citations and the number of papers of a given investigator [2]. The intersection of such curve with the equality straight line produces an index, called H, which is the number of papers that received at least H references in a predetermined period of time. However, such index neglects the contribution of the less cited papers and, as the traditional impact factor, depends strongly on the discipline.

The present article, using Hirsch's nice engineering-like crossing point idea, proposes two new normalized indices, *selectivity* S and *amplitude* A, that are independent on the discipline and that take into account the whole spectrum of published and cited papers..

2. Materials and Methods

A total number of 100 scientists of different levels, from the physical, biological and biomedical sciences, including those studied by Hirsch in his paper, were numerically analyzed. SCOPUS was the database that supplied the number of papers x published by each subject along with the number of citations y per paper. The overall time span started in 1965 reaching 2006, i.e., four decades were considered. Humanities were not included.

For each scientist, a scattergram was drawn showing y on the vertical axis and x on the horizontal one. Thereafter, the cloud of points was fitted to the potential function $y = \mathrm{a}x^{-b}$, calculating also the correlation coefficient r and the crossing point with the equal value straight-line $y = x$ to obtain H from Log H = Log a/(1 + b).

As expected, each author has always one paper ($x = 1$) with a maximum number of citations N_{max} and a number M of papers with just 1 citation ($y = 1$), thus anchoring the curve on these two extreme points (Fig. 1). Values in-between should on the average decrease monotonically. Besides, we define *selectivity* S as

$$S = (N_{\max} - H)/H \tag{1}$$

and *amplitude* or *width* or *reach* A as

$$A = (M - H)/H \tag{2}$$

Both parameters were scaled to H, using each individual as his/her own reference, thus making them independent on the scientist's discipline (Fig. 1). Thereafter, the relationship S/A was computed for each researcher. Besides, the overall average correlation coefficient, its standard deviation SD and range (difference between maximum and minimum values) were obtained.

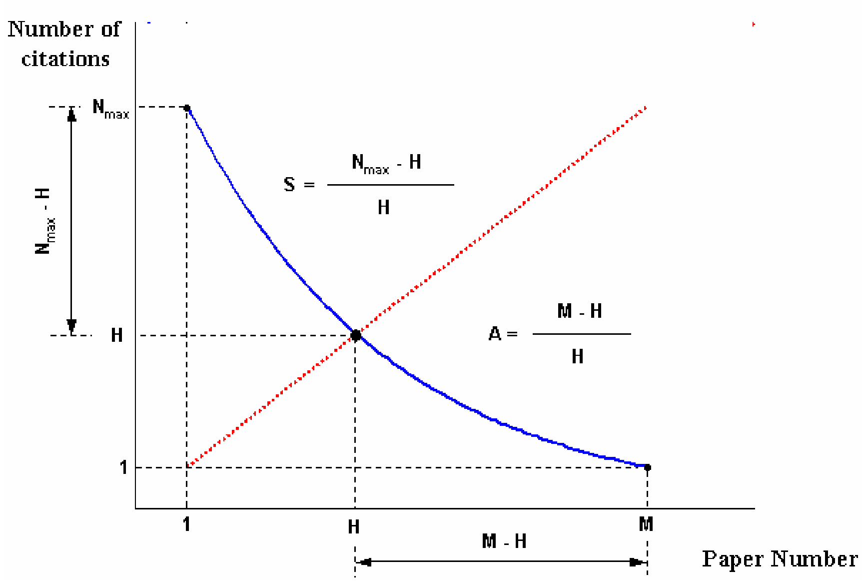


Figure 1. Number of citations on the vertical y-axis versus number of papers on the horizontal axis x. The curve "hangs" from points (1, N_{max}) and (M, 1), decreasing monotonically. The equal value straight line is also displayed with the crossing point that produces the value H, as defined by Hirsch.

Figure 2 identifies three probable different expected behaviors, that is,

- Type A: A symmetric curve depicting an *equilibrated scientist*;

- Type B: A sharp, narrow and non-symmetric curve shifted to the left, which would describe a *highly selective scientist* who is well known in the community and cited in a very specific subject; and

- Type C: A short curve on the left and rather extended towards the right hand side of the graph, depicting a scientist who is not outstanding in any specific subject but, otherwise, has been considered with many papers (*amplitude* or *width*).

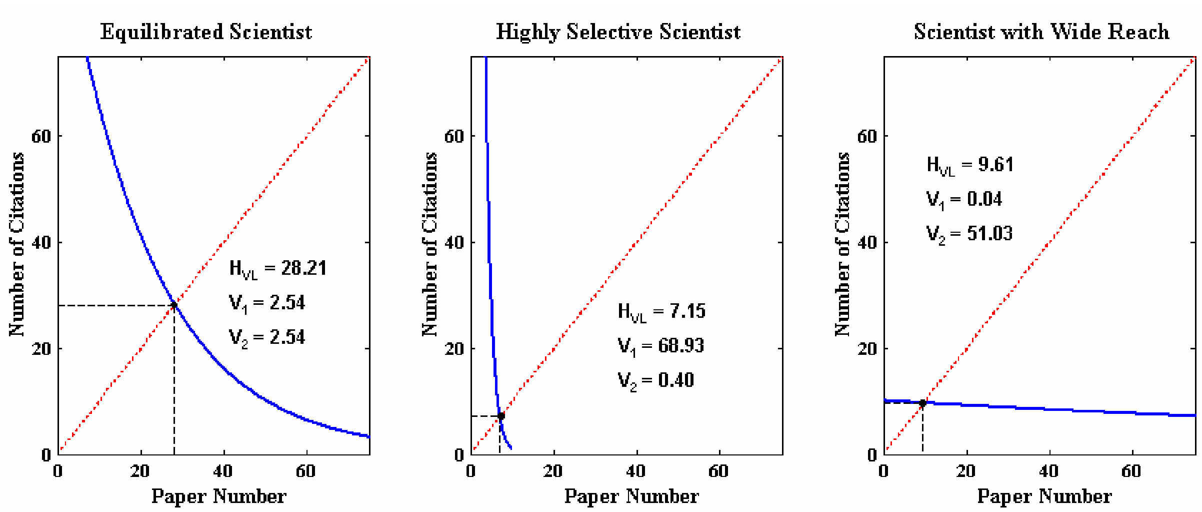


Figure 2. Three possible hypothetical behaviors: On the left side, an equilibrated scientist (Type A); on the center, a highly selected one (Type B); and on the right, a scientist with wide reach and low selectivity (Type C). The numerical values shown on the figure were chosen to produce the described behaviors.

Moreover, out of the overall sample, 40 cases were randomly chosen as a subsample to test four other fits in order to asses their appropriateness, namely, hyperbolic, exponential, parabolic and cubic. It should be pointed out that the potential function coincides with the hyperbolic when the exponent b = 1; some real cases may fall in this particular situation. It should be underlined that the hyperbola used by Hirsch [2] is shifted upward and to the right, that is, it follows the form $y = k/(x - x_o)$.

3. Results

Tables 1, 2 and 3 summarize the results obtained from scientists who acted in three wide areas (Exact and Natural Sciences, with 27 subjects; Biomedical Sciences, with 46 subjects; and Engineering and Technological Sciences, with 27 subjects). Names are ordered following the decreasing values of S/A (6^{th} column). Simple inspection clearly shows an overall tendency to selectivity.

Figure 3 shows two cases representing approximately the first category described above. The difference between the two is the width of the curves reflecting how wide and selective these individuals were with their respective productions. Figures 4 and 5 depict, respectively, the selective and the ample researcher.

Figure 6 compares, out of the subset of 40 cases anticipated above, adjustments other than the potential function made with the data of two researchers listed in the tables. Hirsch´s shifted hyperbola (not shown) always produce H values higher than the others.

Journal of Physics: Conference Series **90** (2007) 012018 doi:10.1088/1742-6596/90/1/012018

Table 1. List of 27 scientists who produced papers in the indicated area. Most of them are physicists. Columns from left to right: Name, H index calculated with Hirsch's hyperbola, H calculated with the potential fit, selectivity S, amplitude A, S/A ratio, correlation coefficient of the fit, observations.

EXACT & NATURAL SCIENCES							
Name	**H(h)**	**H**	**S**	**A**	**S/A**	**r**	**Observations**
Vafa, C	66	4,82	165,51	0,04	4342,63	0,4608	from Hirsch´s paper
Anderson, P.W.	91	3,57	427,23	0,12	3551,76	0,5851	from Hirsch´s paper
Grigera, J.R.		3,70	481,09	0,62	773,10	0,6286	Fellow Investigator - CONICET (Arg)
Hawking, S.W.	62	3,70	56,83	0,08	702,33	0,5005	from Hirsch´s paper
Bahcall, J.N.	77	6,22	67,29	0,12	539,06	0,6454	from Hirsch´s paper
Pallotti, G.		1,76	45,11	0,14	325,85	0,6742	University of Bologna, Italy
Louie, S.G.	70	5,58	144,68	0,61	236,14	0,8145	from Hirsch´s paper
Scalapino, D.J.	75	6,24	100,44	0,44	227,09	0,6562	from Hirsch´s paper
Jackiw, R.	69	4,21	37,96	0,19	202,09	0,6827	from Hirsch´s paper
deGennes, P.G.	79	6,51	69,40	1,15	60,24	0,7747	from Hirsch´s paper
Heeger, A.J.	107	10,74	121,40	2,26	53,71	0,8479	from Hirsch´s paper
Wilczek, F.	68	5,48	109,88	2,47	44,58	0,7257	from Hirsch´s paper
Grosse, C.		4,00	10,00	0,25	39,96	0,6554	Senior Investigator - CONICET (Arg)
Gross, D.J.	66	4,53	30,12	0,99	30,54	0,6984	from Hirsch´s paper
Blesa, M. A.		5,07	15,17	0,58	26,25	0,7566	Fellow Investigator - CONICET (Arg)
Previtali, C. M.		4,80	6,29	0,25	25,15	0,5374	Fellow Investigator - CONICET (Arg)
Cohen, M.L.	94	5,48	14,69	0,64	22,87	0,8439	from Hirsch´s paper
Dresselhaus, M.S.	62	9,69	100,84	4,57	22,06	0,8599	from Hirsch´s paper
Parisi, G.	73	6,84	21,07	1,78	11,86	0,8165	from Hirsch´s paper
Cardona, M.	86	10,20	28,62	3,02	9,47	0,8730	from Hirsch´s paper
Rúveda, E.A.		3,37	8,48	1,07	7,90	0,8530	Fellow Investigator - CONICET (Arg)
Gossard, A.C.	94	10,13	30,58	5,91	5,18	0,8839	from Hirsch´s paper
Maple, M.B.	66	9,13	28,01	5,46	5,13	0,9238	from Hirsch´s paper
Castagnino, M. A.		3,92	6,66	1,55	4,29	0,7942	Fellow Investigator - CONICET (Arg)
Herbst, R.		3,54	2,11	0,70	3,03	0,7018	Fellow Investigator - CONICET (Arg)
Fisk, Z.	75	10,07	35,25	13,90	2,54	0,8949	from Hirsch´s paper
Valentinuzzi, M.E.		4,20	5,90	3,28	1,80	0,8664	IEEE Fellow
Mean		**5,70**	**81,14**	**2,24**	**417,65**	**0,74**	
STD		**2,39**	**116,91**	**4,32**	**1045,38**	**0,13**	

Table 2. List of 46 scientists who produced papers in the indicated area. Columns as in the previous table, except H(h) for which values were not calculated.

BIOMEDICAL SCIENCES						
Name	**H**	**S**	**A**	**S/A**	**r**	**Observations**
Baan, J.	5,20	68,68	0,15	443,51	0,7145	Leiden University, Netherlands
Boveris, A. A.	6,58	255,87	0,82	310,15	0,7620	Fellow Investigator - CONICET (Arg)
Crick, F. H.C.	3,81	92,02	0,31	293,20	0,6258	Nobel Prize
Felice, C. J.	2,91	8,97	0,03	281,99	0,5818	Junior Senior Investigator - CONICET (Arg)
De Bold, A.	4,52	140,32	0,77	182,40	0,7201	Fellow Investigator - CONICET (Arg)
Kass, D. A.	7,67	88,22	0,57	156,07	0,7761	Johns Hopkins University
Savino, G. V.	1,86	9,22	0,08	121,75	0,9743	Junior Investigator - CONICET (Arg)
Wiley, V.	3,07	36,12	0,30	119,47	0,7181	Hospital of Westmead, Australia
Wilkins, M.H.	2,49	23,10	0,21	112,63	0,7996	Nobel Prize
De Mendoza, D.	4,00	19,75	0,25	78,93	0,7971	Senior Investigator - CONICET (Arg)
Morero, R.	3,68	6,34	0,09	72,79	0,6388	Senior Investigator - CONICET (Arg)
Braunwald, E.	11,63	386,68	5,97	64,82	0,8296	Harvard University, Boston, USA
Maggio, B.	5,65	11,56	0,24	48,47	0,7036	Fellow Investigator - CONICET (Arg)
Uchitel, O.D.	3,83	34,75	0,83	42,03	0,7118	Fellow Investigator - CONICET (Arg)
Guillemin, R.	5,63	116,85	3,08	37,91	0,8545	Nobel Prize
Pasquini, J. M.	4,31	14,78	0,39	37,68	0,8146	Fellow Investigator - CONICET (Arg)
Birnbaumer, L.	7,67	48,41	1,35	35,95	0,7942	NIH, USA
Soto, E.F.	3,96	16,19	0,77	21,04	0,8674	Fellow Investigator - CONICET (Arg)
Luly, P.	3,64	7,53	0,38	20,07	0,7137	University of Rome Tor Vergata, Italy
Wolosiuk, R.	4,13	8,70	0,45	19,14	0,6154	Fellow Investigator - CONICET (Arg)
Torres, H.	4,60	9,64	0,52	18,53	0,8100	Fellow Investigator - CONICET (Arg)
Catt, K. J.	10,99	28,22	1,64	17,21	0,8728	NIH, USA
Mordoh, J.	4,03	27,03	1,73	15,64	0,7824	Fellow Investigator - CONICET (Arg)
Maccioni, H.	4,59	8,80	0,74	11,85	0,6540	Fellow Investigator - CONICET (Arg)
Charreau, E. H.	5,18	17,52	1,70	10,30	0,8454	Fellow Investigator - CONICET (Arg)
Miceli, D.	2,77	4,42	0,45	9,91	0,6366	Senior Investigator - CONICET (Arg)
De Nicola, A. F.	6,18	11,45	1,26	9,06	0,7665	Fellow Investigator - CONICET (Arg)
Barrantes, F. J.	5,52	8,59	0,99	8,67	0,8521	Fellow Investigator - CONICET (Arg)
Geddes, L.	7,45	48,13	6,11	7,87	0,8562	Purdue University, USA
Sterin-Borda, L. J.	6,74	13,40	1,82	7,36	0,9260	Fellow Investigator - CONICET (Arg)
Farías, R. N.	5,00	11,41	1,60	7,12	0,8379	Fellow Investigator - CONICET (Arg)
Podestá, E. J.	4,85	5,39	0,86	6,30	0,8718	Fellow Investigator - CONICET (Arg)
Affanni, J.	3,80	6,63	1,11	6,00	0,8682	Fellow Investigator - CONICET (Arg)
Libertun, C.	5,34	6,49	1,62	4,00	0,8140	Fellow Investigator - CONICET (Arg)
Weissenbacher, M.	4,90	10,82	2,87	3,77	0,7778	Fellow Investigator - CONICET (Arg)
Segura, E. T.	3,40	6,05	1,64	3,68	0,8165	Senior Investigator - CONICET (Arg)
Coussio, J.	5,32	5,20	1,63	3,19	0,7945	Fellow Investigator - CONICET (Arg)
Garrahan, P. J.	4,24	7,96	3,01	2,65	0,8492	Fellow Investigator - CONICET (Arg)
Moguilevsky, J. A.	4,78	9,47	4,03	2,35	0,8034	Fellow Investigator - CONICET (Arg)
Goñi, F. M.	7,03	42,26	19,92	2,12	0,8445	Universidad del Pais Vasco, Bilbao, Spain
Cardinali, D.P.	9,01	6,88	4,66	1,48	0,9225	Fellow Investigator - CONICET (Arg)
Calandra, R. S.	4,98	3,42	2,82	1,21	0,8775	Fellow Investigator - CONICET (Arg)
Martínez Ríos, M. A.	3,74	4,88	4,34	1,12	0,9251	Instituto Nacional de Cardiología, Mexico
Yalow, R. S.	5,41	5,29	4,92	1,08	0,9145	Nobel Prize
Bravo González, J.	2,37	1,11	1,95	0,57	0,7026	Instituto de Medicina Tropical P. Kourí, Cuba
Aguera Fernández, L. G.	2,43	1,06	1,88	0,56	0,9989	Hospital Reyes Católicos, Burgos, Spain
Mean	**5,02**	**37,08**	**2,02**	**57,90**	**0,80**	
STD	**2,05**	**69,92**	**3,12**	**97,81**	**0,10**	

Table 3. List of 27 scientists who produced papers in the indicated area. Columns as in the first table, except H(h) for which values were not calculated.

ENGINEERING & TECNOLOGICAL SCIENCES						
Name	**H**	**S**	**A**	**S/A**	**r**	**Observations**
Hirosaki, Botaro	1,74	33,50	0,15	223,27	0,7649	IEEE Fellow
Chiacchiarini, Héctor G.	1,84	8,24	0,09	94,14	0,9560	Junior Investigator - CONICET (Arg)
Long, Stuart A.	3,82	42,95	1,62	26,58	0,7363	IEEE Fellow
Sanderson, Arthur C.	5,45	30,36	1,57	19,37	0,8299	IEEE Fellow
Matsuse, Kouki	4,42	36,10	1,94	18,60	0,8079	IEEE Fellow
Bonissone, Piero P.	2,99	11,71	0,67	17,43	0,8583	IEEE Fellow
Bonnett, Austin	3,45	22,47	1,32	17,05	0,8653	IEEE Fellow
Habetler, Thomas	5,52	24,56	1,54	15,97	0,8131	IEEE Fellow
Signorelli, Javier W.	2,36	3,23	0,27	12,01	0,8867	Junior Investigator - CONICET (Arg)
Jardini, José Antonio	1,95	5,68	0,54	10,48	0,6872	IEEE Fellow
Elaskar, Sergio A.	2,23	3,03	0,34	8,80	0,9553	Junior Investigator - CONICET (Arg)
Bridger, Baldwin	2,31	6,36	0,73	8,69	0,8598	IEEE Fellow
Siñeriz, Faustino	4,48	11,49	1,45	7,91	0,8814	Fellow Investigator - CONICET (Arg)
Tranter, William H.	2,84	4,29	0,76	5,62	0,7822	IEEE Fellow
Sikora, Jorge Antonio	3,07	1,61	0,30	5,28	0,7467	Senior Investigator - CONICET (Arg)
Bose, Bimal K.	4,92	12,41	2,45	5,06	0,8587	IEEE Fellow
Jagadish, Chennupati	8,04	17,16	3,48	4,93	0,8257	IEEE Fellow
Doughty, Richard L.	2,92	4,81	1,05	4,58	0,8167	IEEE Fellow
Geiger, Randall L.	4,82	15,41	4,19	3,68	0,8191	IEEE Fellow
Buitragó, Roman H.	2,72	4,15	1,21	3,44	0,8693	Senior Investigator - CONICET (Arg)
Panayirci, Erdal	3,50	4,42	1,57	2,82	0,9213	IEEE Fellow
Love, Daniel J.	2,10	3,77	1,39	2,72	0,7192	IEEE Fellow
Cascone, Osvaldo	4,39	4,69	1,73	2,71	0,8673	Senior Investigator - CONICET (Arg)
Hsia, T. C. Steve	4,77	6,97	2,78	2,51	0,9204	IEEE Fellow
Carver, Doris	2,43	1,88	1,06	1,78	0,9458	IEEE Fellow
McClung, L. Bruce	2,15	1,32	1,32	1,00	0,9873	IEEE Fellow
Laura, Patricio	7,34	4,72	7,99	0,59	0,9200	Fellow Investigator - CONICET (Arg)
Mean	**3,65**	**12,12**	**1,61**	**19,52**	**0,85**	
STD	**1,64**	**11,83**	**1,61**	**44,45**	**0,08**	

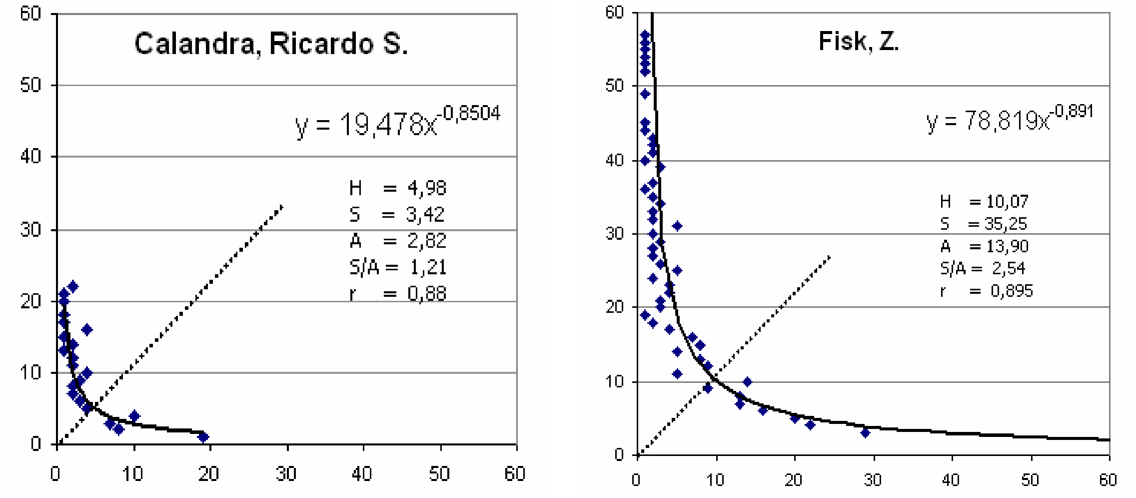


Figure 3. Rather equilibrated scientists. That on left extends from 20 to 20 while that at the right goes from 60 to 60. The latter tends to be more selective; both had curve fits with high correlations.

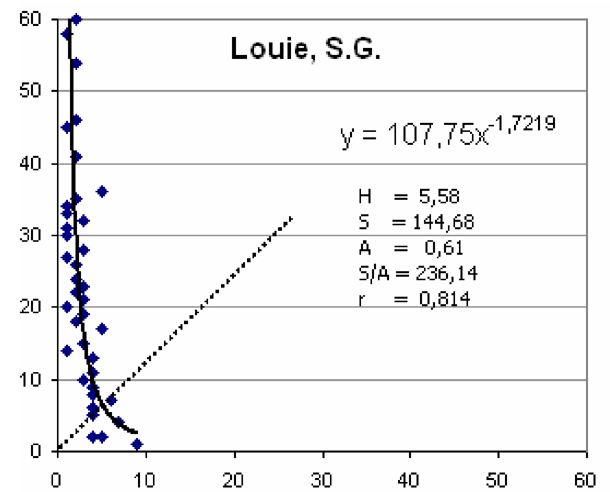


Figure 4. Good example of selectivity. Amplitude is rather small, while the correlation is high.

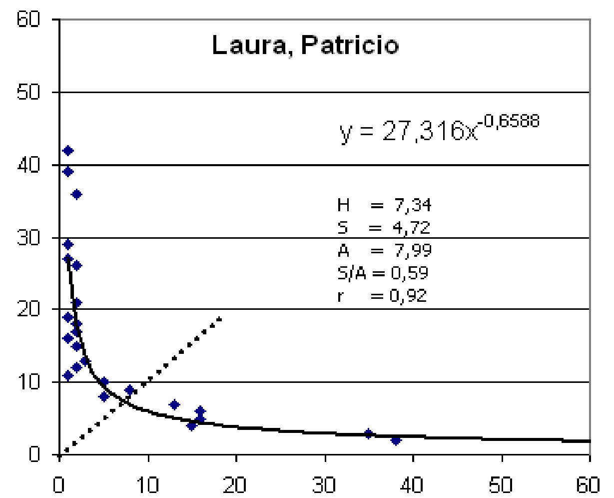
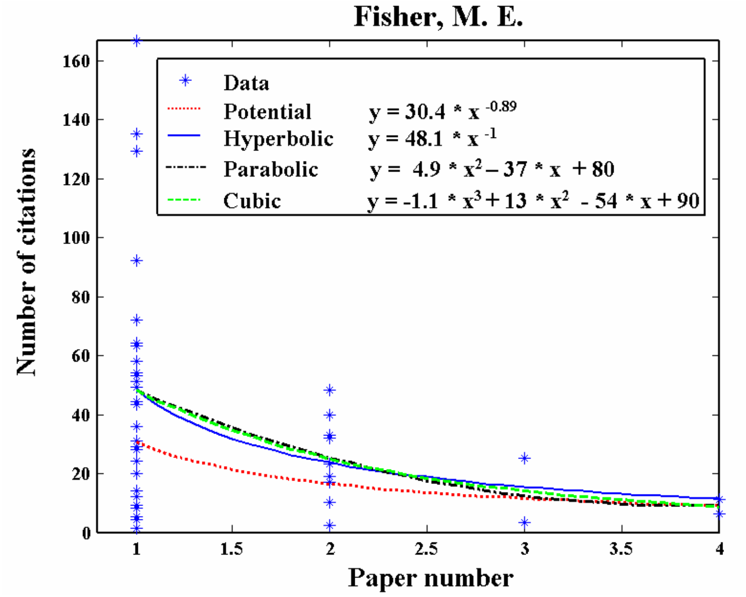


Figure 5. Example of amplitude. Observe the S/A ratio lower than 1. Correlation is high.



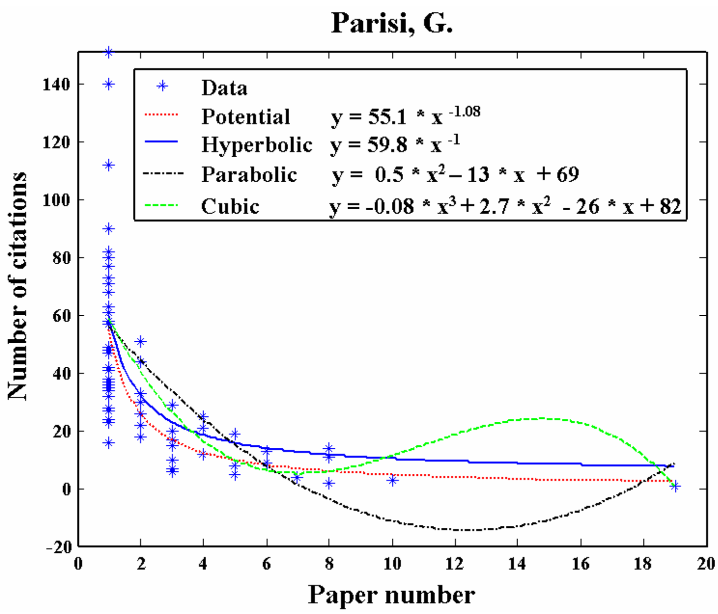


Figure 6. Two cases, whose numerical values for the potential fit can be found in the tables and that belong to the sub-sample of 20 mentioned in Materials and Methods, are depicted here. The best adjustment is achieved with the potential fit.

4. Discussion

Quantitative evaluation of research output is a delicate subject which has elicited different responses from the worldwide scientific community, some of them rather controversial or even in definite opposition [3]. Obviously, the main product an investigator is supposed to give out are papers of the best possible level [4]-[5] and most of the time committees concentrate mainly on them, but there are aspects clearly not covered by the proposed indices, such as organization of societies, laboratories, institutes, research and graduate programs, journals, congresses or the like that a person in academics may have produced in his/her life, which represent no doubt curricular assets. Moreover, there is abundant literature alerting us that citation counts should be used with care for evaluating the quality of individual scientists. On the contrary, citation data is currently used in specialized areas such as dynamic mapping of science, the identification of research fronts, the study of scientists' networks, invisible colleges or authors' networks, among others. Thus, we underline the concept of complementary elements of these numerical indices for the evaluation process, in the sense that citation analysis can not replace peer review. The evaluating committee, based on the curriculum vitae, the needs of the specific position to be filled, and a responsible use of all such varied information is the only one able to reach the best and adequate decision regarding a given candidate.

The method herein proposed, after the results shown above, clearly points out to the potential function as the best fit to the data: the line traverses in every case through the middle of the cloud of points leaving roughly one half above it and the other half below; even some of them lie just on the line. Correlation coefficients were always high (in the order of 0.79 ± 0.11, with a coefficient of variation of 13.6 %; see the tables).

In spite of its discipline-dependency, a short discussion regarding the H index seems appropriate. Its value falls about one order of magnitude when the fitting is done with the potential function (compare the 2nd and 3rd columns in those rows where the scientists were chosen from Hirsch's paper, that is, H(h) versus H). Averages (± the standard deviations SD) were 5.7 ± 2.39 for the Exact & Natural Sciences, 5.02 ± 2.05 for the Biomedical Sciences, and 3.65 ± 1.64 for the Engineering Sciences, so bringing the values closer together; their respective coefficients of variation are 88.5%, 40.8% and 44.9%; the latter large spreads should be expected because the sample includes scientists of different levels. However, the new raw H index appears as better bounded. The difference is no surprise, too, because Hirsch's hyperbola is shifted upwards and to the right as compared to the potential function. The range according to the original H(h) is 62-107, for highly outstanding physicists [2], while the potential H was 1.76-10.74, for the Exact & Natural Sciences; 1.86-11.63, for the Biomedical Sciences; and 1.74-8.04 for Engineering and Technology. The relatively small overall range (1.74-11.63) gives the impression that the H index *per se* might be used for comparisons, disregarding the discipline. If so, the question would be how to demonstrate or disprove the hypothesis.

Normalization to the individual H permits interdisciplinary comparisons, and that appears as a remarkable feature. What we calculate is how many times each H enters into either the difference between the maximum citations and H or between the maximum number of papers with one citation and H; thus, each researcher acts as his/her own reference. Most of the authors displayed a marked selectivity, which should not surprise the reader because a typical researcher concentrates only on just a single subject or perhaps a mere few while a wide reach to the right side of the graph did not predominate.

One question we may pose refers to who has performed better. Perhaps highly selective or equilibrated scientists are desirable. Certainly, the third type will never be a candidate for the Nobel Prize for he/she did not obtain an outstanding number of citations in one or two papers. None the less, the latter may illustrate on a good teacher with didactic talent and abilities. Depending on institutional or disciplines' needs, the evaluating committee may find him or her as the right candidate for the post to be filled.

With the birth of virtual journals, the number of accesses to published articles has become a popular piece of information. Accesses indicate that at least the paper called attention, its title was read, maybe its summary or maybe the entire article. Thus, the number of accesses should be considered another way of measuring impact. The scattergram to be fitted now would be number of accesses versus number of papers.

The method and indices herein proposed can be applied also to grade the ability the candidate had to obtain research grants. Simply represent on the vertical axis the amount in dollars of each grant and on the horizontal axis the number of grants he/she got. That would be quite a piece of solid quantitative information. Laboratories, institutes or journals are also candidates to be evaluated by the methodology herein described.

In conclusion, the method and its set of parameters can no doubt be proposed as a numerical way to complement the evaluation process of a potential candidate to a given position.

Acknowledgments
This study was supported by CONICET (*Consejo Nacional de Investigaciones Científicas y Técnicas*; National Research Council of Argentina). The authors express their special recognition to Ms. Cynthia Jeppesen, BS, MS, and manager of the Evaluations Department (*Gerencia de Evaluaciones*) of CONICET for her support, appropriate comments and critical discussion. We specially are grateful to Mr. Alfredo A. Pisano for the tiring task of searching the database and ordering the information. This paper was communicated to the XVI Congreso Argentino de Bioingenieria, San Juan, Argentina, Sept 26-28, 2007.

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