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An analysis of international mobility and research productivity in computer science

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Abstract

In this article, we study the international mobility of researchers in the field of computer science (CS). Our analysis hinges upon Scopus data spanning a time period of 30 years (1991–2020) and involves a total of 969,835 researchers and 8,412,543 publications. Our contribution is two-fold. First, we characterize mobility as a fairly common phenomenon in CS, we highlight a strong correlation with standard bibliometric indicators at all seniority levels and a lower propensity of female researchers to relocate internationally than their male colleagues. Second, we analyze individual career paths building from them a mobility graph and identifying common patterns, such as the most traveled connections between different countries, whether they are equally traversed in both directions and the most frequently visited countries. The temporal evolution of the above patterns within our 30-year time frame is also investigated. The United States emerged as a preferred destination for internationally mobile authors, with strong connections to China (from the early 2000s), Canada, and several prominent European countries, most notably the United Kingdom, Germany, and France.

Keywords Computer science research · Geographical mobility of researchers · Correlation between geographical mobility and scientific productivity · Time evolution of mobility patterns

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Introduction

Investigating the dynamics of research communities is important in order to gain insight into the development trends of different domains. In particular, the mobility of researchers appears to be an important component in the production of scientific knowledge and can have a significant impact on research productivity. Researchers' mobility is influenced by complex factors (e.g., country of origin, gender, academic seniority, research field) and could open up new research opportunities (e.g., access to funding, equipment, or expertise not available in the home country). In turn, this could help researchers advance their careers and increase their research impact. In fact, mobility can lead to the creation of new research collaborations, the exchange of knowledge and ideas, and the development of novel approaches. Building international research networks, in particular, might improve the chances of securing funding, publishing in prestigious venues, and obtaining higher bibliometric indicators. We remark that indicators such as the number of citations or h-index are more and more often, and not without controversy, used in research evaluation efforts throughout the world, both at the level of research institutions for purposes of funds allocation (see, e.g., Demetrescu et al., 2019, 2020; Franceschini & Maisano, 2017; Kulczycki, 2017; Stuart, 2015), and at the level of individual researchers for career advancement (see, e.g., (Demetrescu et al., 2020; Smith et al., 2013).

In this article, we focus on computer science (CS) research. While being a relatively young discipline, CS has a huge impact on many other research fields and on society in general, being a key component of current technological developments. CS as a research field has been growing at a staggering rate over the past 30 years, with scientific productivity (and its growth rate) distributed somewhat unequally between countries (Demetrescu et al., 2022). This uneven distribution, in turn, sparks a strong interest in the study of the international mobility of CS researchers.

To carry out our analysis, we rely on data extracted from Scopus, which is one of the most prominent bibliographic repositories worldwide[1]. We try to answer a variety of different questions. How frequent is international mobility in CS? Is it equally distributed between male and female researchers or is there a gender imbalance? Is there a correlation between international mobility and research productivity of CS researchers? What are the patterns of researchers' international travels (e.g., the busiest connections between nations or the most frequently visited countries)? Do these patterns evolve over time? And do they change when only top scientists are considered? Our analysis spans a 30-year period, from 1991 to 2020, and involves a total of 969,835 researchers and 8,412,543 publications.

The main findings of our investigation can be briefly summarized as follows. International mobility among CS scientists is a fairly common phenomenon, and it strongly correlates with research productivity, measured in terms of standard bibliometric indicators. Although increasing academic age plays a role in this correlation, there is strong evidence that it cannot be its only cause. Female researchers are slightly less inclined than their male colleagues to relocate abroad. Our analysis of individual career paths, from which a mobility graph is obtained, places the United States as a central hub for international mobility in CS. The United States are by quite a margin the preferred destination for researchers relocating abroad, and even more so when considering top scientists. The most traveled routes are those connecting the United States with China (from the early 2000s onward),

[1] This work uses Scopus data provided by Elsevier through ICSR Lab.

Canada, and some prominent European countries, such as the United Kingdom, Germany, and France. In the last two decades, China has also enjoyed a solid relationship with Hong Kong.

Structure of the article The remainder of this article is structured as follows. The second section surveys related work. Our datasets, our approach, and some of their limitations are discussed in "Datasets and approach" section. "Correlation between mobility and productivity" section investigates the correlation between the international mobility of CS authors and their scientific productivity. "International career paths" section extracts global trends from individual career paths. Our findings are discussed in "Discussion" section, while "Concluding remarks and future research" section presents concluding remarks and outlines future research directions.

Related work

There is a significant body of academic research on the mobility of scientific researchers, exploring various aspects of the phenomenon from different angles and using both qualitative and quantitative methods. The majority of works focus on mobility versus productivity issues, mostly for selected disciplines, while a few of them also relate mobility to aspects such as career advancements or change of research topics. Some works address worldwide mobility (see "Worldwide mobility" section), while many others focus on specific countries or geographical areas (see "Mobility for selected countries" section).

Worldwide mobility

Netz et al. (2020) present a systematic review of the literature on how international mobility affects the career of scientists. In this meta-analysis, they considered 96 studies, published between 1994 and 2019. When it comes to the influence of international mobility on productivity and impact, they find contrasting results in the literature: most studies report positive effects, but others detect no or even negative effects. The mobility of European scientists to the US appears to have a greater impact on productivity than intra-European mobility (Van Bouwel & Veugelers, 2014). In addition, in general, mobility to larger countries that are prone to research tends to be more productive (Gibson & McKenzie, 2014). There is also some evidence that short stays are more beneficial than long ones (Decramer et al., 2013). Netz et al. (2020) argue that many studies only insufficiently address the bias resulting from the fact that those traveling abroad are not necessarily a random sample from the author population, at least with respect to their productivity. Similar conclusions are also drawn for studies that deal with the relation between international mobility and scientific impact.

Similarly, Paraskevopoulos et al. (2021) take into consideration 81,500 authors from all disciplines, with publication data extracted from Scopus. They investigate the connections between the structure of the academic collaborations, researchers' productivity and impact, and researchers' mobility (both domestic and international). Their findings are as follows. Up to a certain performance level, the correlation between collaboration network size and productivity/impact of research is high, while the correlation diminishes for the top performing scientists. Internationally mobile authors seem more efficient at exploiting large collaboration networks for increased productivity, while domestically mobile authors are more effective at using them to boost their research impact. Finally, a lack of payoff is observed for very high mobility, as its correlation with research impact is smaller than for regular authors.

Many other works focus on multiple disciplines or specific ones. We highlight some of them below.

Multiple disciplines

Franzoni et al. (2014) focus on 14,299 researchers active in four disciplines (biology, chemistry, earth and environmental sciences, materials science). Evidence of better performance by migrant scientists emerges. The authors also take measures to mitigate the effect of positive selection in migration, which may occur under the assumption that only the most capable are offered opportunities advantageous enough to outbalance the cost of relocation. The superior performance of migrant scientists is found to persist, suggesting that migration may be a likely cause for the observed performance boost.

Halevi et al. (2016) investigate whether there is a relationship between the mobility of authors and their productivity and impact by examining 100 top-publishing authors from neuroscience, mechanical engineering, arts and humanities, oncology, environmental geology, business, infectious diseases, in the time period 2010–2015. They find that in most disciplines, having two different affiliations in an author's career increases productivity. A third affiliation may increase citations. The effect of country mobility instead seems to be more limited, in terms of both productivity and impact.

Horta et al. (2022) focus on a sample of 7158 academics from many countries and disciplines, with at least an international publication in the time frame 2010–2016. Rather than scientific productivity or impact, they compare creativeness, innovativeness, and willingness to change research topics of mobile academics, homegrown academics (those spending their entire career in a single institution), and silver-cord academics (those moving only once and then get back to their original institution). Homegrown academics are found to be less innovative, ambitious and adaptable than mobile ones, with silver-corded academics lying somewhere in between.

Specific disciplines

Dubois et al. (2014) concentrate on 32,574 mathematicians from all over the world active in the time period 1984–2006. They draw a number of conclusions. The productivity of mathematicians does not seem to decline significantly with age. On the other hand, there is a substantial attrition rate (i.e., mathematicians that stop publishing) at any age. International mobility after PhD is found to be a rather weak phenomenon, and much more symmetric than expected, both in terms of quantity and "quality" of mathematicians who change countries. However, it is found to be beneficial, with future scientific production increasing with each move. Larger departments are determined to improve individual productivity. Collaborations, on the other hand, are found to be beneficial only if they are among authors from different specialties (within the field of mathematics).

Albarran et al. (2017) focus on a sample of 2605 highly productive economists taken from the faculty members working in 2007 in the top 81 economics departments worldwide (according to the Econphd-2004 university ranking). Of the selected departments, 52 are in the US, 22 in EU member countries, 4 in Canada, 2 in Israel and 1 in China. The authors observe a clear "funneling effect" whereby highly productive researchers are attracted towards the US. The dominance of US institutions in the field of economics, with a world share output of 75.6%, is quite marked, whereas the world share output of researchers born in the US is set at a lower 51.8%. This suggests that a relevant fraction of the research output of US institutions may be due to migrant scientists.

Deville et al. (2014) focus on the institution-level mobility of 2725 physicists who started their career between 1950 and 1980 and enjoyed a high career longevity (i.e., they published for at least 20 years without any interruption exceeding 5 years). They find that movements are common, yet infrequent: most researchers move only once or twice, usually in the early stages of their career. They also report that geography plays an important role, with most detected movements being local ones, and movements to faraway locations becoming rarer as distances increase. A high degree of stratification is also observed: researchers from elite institutions are most likely to move to other elite institutions, whereas authors from lower-rank institutions are more likely to move to places with similar rank. When cross-group movements occur, they are usually only associated with modest changes in individual research impact.

Petersen (2018) concentrate on 26,170 researchers, active between 1989 and 2009, who have at least 10 publications in journals edited by the American Physical Society. In particular, they take into considerations, for each mobility event in a researcher's career, the five years before and the five years after the event. By applying statistical matching methods that pair mobile researchers with non-mobile ones that are similar in research profile attributes prior the mobility event, they find that researchers' mobility has a significant positive effect on citation impact and increases diversity in research topics and collaborations.

Mobility for selected countries

Mobility in European countries is addressed by Cañibano et al. (2020) that analyze the link between international mobility and career advancement for a sample of 1995 European researchers. The authors report that international visits of 3 to 6 months are the most common form of mobility. International mobility is more likely to be associated with a change of employer in the early stages of a researcher's career. Career advancements occur in relation to mobility events only in about 15% of all cases. Prior mobility is found to be strongly associated with career advancement in the early career stages, while return mobility is associated with career advancement in later career stages.

Most of the other works focus on specific countries. Aksnes et al. (2013), for instance, concentrate on 11,465 Norwegian scientists from all fields of research. First, they remark that immobility is the normal case, with only a minority of authors working for two or more institutions during their career. They find that domestic mobility seems to have only a small impact on publication and citation rates, while the benefits of international mobility appear more marked. The authors remark that their study proves no cause-effect relationship with regards to the correlation between mobility and scientific productivity.

A multidisciplinary study is also presented by Horta et al. (2019) that investigate both educational and career mobility for researchers based in Hong Kong and Macau. Their analysis is based on data collected from an online questionnaire live between December 2015 and February 2016, and includes 408 authors. The main conclusion is that although mobility has mostly positive effects on research output, the association is complex and nuanced. In particular, the relation between mobility and productivity seems to be nonlinear (i.e., beneficial only up to a certain mobility threshold). Jobs outside of academia may decrease the number of publications, but increase the chances of publishing in top-tier journals. Transnational educational mobility, while providing some advantages, is not essential. Transnational career mobility seems to be more important for academics in STEM fields than for those in non-STEM fields. Caveats include the lack of accurate information about the duration and location of the mobilities investigated, and the fact that the analysis is correlational rather than causal.

Many other works are in specific disciplines. Hard sciences are the topic of Abramo et al. (2022) that study Italy's domestic mobility and its relation with scientific productivity. They focus on Italian academics on national mobility between 2009 and 2014 (568 scientists in all), evaluating their research performance in the 5-year period before the transfer and in the 5-year period after the transfer. It is shown that less productive researcher are more likely to move than more productive ones, and more than half of domestically mobile researchers worsen their academic performance after relocating.

Fernández-Zubieta et al. (2015) examine the careers of 171 UK academic researchers in the time frame 1982–2005 considering four different hard disciplines: chemistry, physics, CS and mechanical, aeronautical and manufacturing engineering. The authors report a high level of institutional mobility: two thirds of the sample moved between institutions at least once, and one third moved two times. It is noted that mobility to higher level institutions has only a weakly positive impact on productivity and none on citations received, while downward mobility tends to negatively affect a researcher's overall performance. It is also remarked that, even in the cases of moves to higher ranked institutions, job changes are often accompanied by temporary decreases in productivity, probably due to adjustment costs.

Life sciences are the subject of Jonkers and Tijssen (2008) that examine 76 top Chinese plant molecular life scientists who moved out of China for a period of their career, and subsequently returned home. They detect a positive impact of the overseas experience on research productivity and international collaborations, more marked for scientists (the majority) who spent their time abroad in North America, as opposed to Western Europe or Japan. Tartari et al. (2020) also take into consideration a sample of 348 researchers active in life science departments of British universities from 1995 to 2009. They formulate and confirm two hypotheses: (1) that researchers experience a gain in productivity when they move to a new university, and (2) that academics moving to a better-endowed department experience a higher gain in productivity than those moving to worse-endowed departments.

Datasets and approach

In this section, we provide details on the datasets used in our study ("Datasets and approach" section) and on our methodology to extract information on international mobility and productivity ("Extracting mobility and productivity data" section). Some caveats and limitations of the current approach, due to characteristics of the datasets exploited in this study, are discussed in "Dataset limitations" section.

Datasets

The authors and publications are based on Scopus data provided by Elsevier through the ICSR (International Center for the Study of Research) Lab. This lab provides extensive data and a cloud-based computational platform, powered by DataBricks, to further the study of research supporting data-driven decisions.

Publications

We have focused on publications, indexed by Scopus, released up to December 31st 2020, whose assigned subject areas include ’Computer Science’ and/or ’Mathematics’. Notice that, in the Scopus classification, “Mathematics” includes the topic “Theoretical Computer Science”, which is of interest in our study. The Scopus database includes 8,412,543 such publications. For each article we maintain its publication year, the citations it has received by March 1st 2021, and the list of all its authors (in the form of Scopus author ids) together with their affiliations, as extracted by Scopus from the publication itself.

Authors

Computer science authors are selected from Scopus by analyzing author records and exploiting the frequency vector of Scopus subject areas present in such records. We have focused on authors that have at least 5 publications with Scopus subject area “Computer Science” (COMP), and such that COMP publications are at least 50% of the highest entry in their subject area frequency vector. The Scopus database includes 969,835 such authors. For each author, we maintain Scopus id, gender, and academic age (see below). Gender is derived from a Scopus table containing an inference of the gender of the authors obtained through a machine learning-based classifier that takes advantage of first name, last name, and country of first affiliation. This inference mechanism—provided by Scopus—appears to be not fully accurate for any single data point, but general trends and overall statistics are meaningful.

Extracting mobility and productivity data

By joining the publications and authors datasets based on matching author ids, we retrieved the list of articles of each author. Since each publication record contains the received citations, we were able to extract individual bibliometric indicators for the entire career of an author, such as average citations per article and h-index, in addition to the total number of publications.

Affiliations

The authors’ affiliations contained in each publication record, as reported in the publication itself, were especially useful in our analyses. By sorting the list of articles of each author according to publication year, we could indeed obtain a time-ordered sequence of <year, affiliation(s)> pairs for each author. It is worth noting that an author can have more than one affiliation in the same year, and this is due to two main reasons. First, an author may have more than one publication indexed in Scopus for a given year, and different publications may report different affiliations. Second, he/she could be affiliated with different institutions, and multiple affiliations may be thus reported even in the same article.

Academic age

Academic age (sometimes abbreviated as *aa* in the sequel) is computed based on the year of the earliest publication indexed in Scopus. More precisely, the academic age of a researcher, in a given year y, is the difference between y and the year of the earliest publication. The seniority levels we consider are inspired by the European Research Council grant levels: we thus focus on academic age ≤ 7, inbetween 7 and 12, inbetween 12 and 25, and larger than 25. Throughout the article, unless otherwise stated, we will assume that academic seniority is calculated w.r.t. 2020, the most recent year included in our analysis (i.e., $y = 2020$).

Dataset limitations

For our analyses we rely on data from Scopus, which is arguably one of the most accurate bibliographic data sources in the world (see, e.g., Baas et al., 2020; Pranckutė 2021). While issues such as multiple author profiles and incorrect authorship attribution may not be completely absent, they are quite rare and should bear no statistically significant impact on our results, which reflect trends over large populations of authors.

Authors' affiliations at the time of writing are more critical. As observed in "Extracting mobility and productivity data" section, authors' affiliations stored in Scopus publication records are extracted from the publications themselves. It is not uncommon that the same affiliation is written using different formats in different publications, even by the same author. Although Scopus has an entity resolution algorithm designed to handle these situations, different affiliation wording may yield incorrect associations. We remark that in this article we are concerned only with affiliation countries and not with affiliation institutions, and therefore the aforementioned issue is only a minor concern: we indeed observed that it is extremely rare that the affiliation country is reported incorrectly, as compared with the affiliation institution.

Using authors' affiliations obtained from the publication records has another important implication: we only consider a type of mobility that is reflected in an author's list of affiliations. It is possible that the authors may visit fellow researchers abroad for relatively short spells without formally changing affiliation. In the present work, we ignore this short-term mobility, as it does not emerge directly from the available data.

As stated in "Datasets and approach" section, for all considered publications we maintain received citations at a specific date (namely, March 1st 2021), regardless of their release year. This potentially puts publications (and consequently the authors who wrote them) in an increasingly disadvantaged position the closer their release year is to our set date, because of the shorter time span available to accumulate citations. However, as often reported in the literature (see, e.g., Pradhan et al., 2019; Walters, 2011), a large number of publications that accumulate significant citations tend to do so within a few years of their release, in a peak period, which is then followed by a declining phase. This should be regarded as a mitigating factor against the above bias, except for the most recent publications.

Correlation between mobility and productivity

The mobility of researchers and their scientific productivity and impact are generally found to be positively correlated in the majority of previous studies. Only a minority of the works report no correlation, or even a negative correlation, while some researchers point out that correlation—or lack thereof—may be discipline dependent (we refer the reader to Netz et al. (2020) for a systematic review of the literature on this topic).

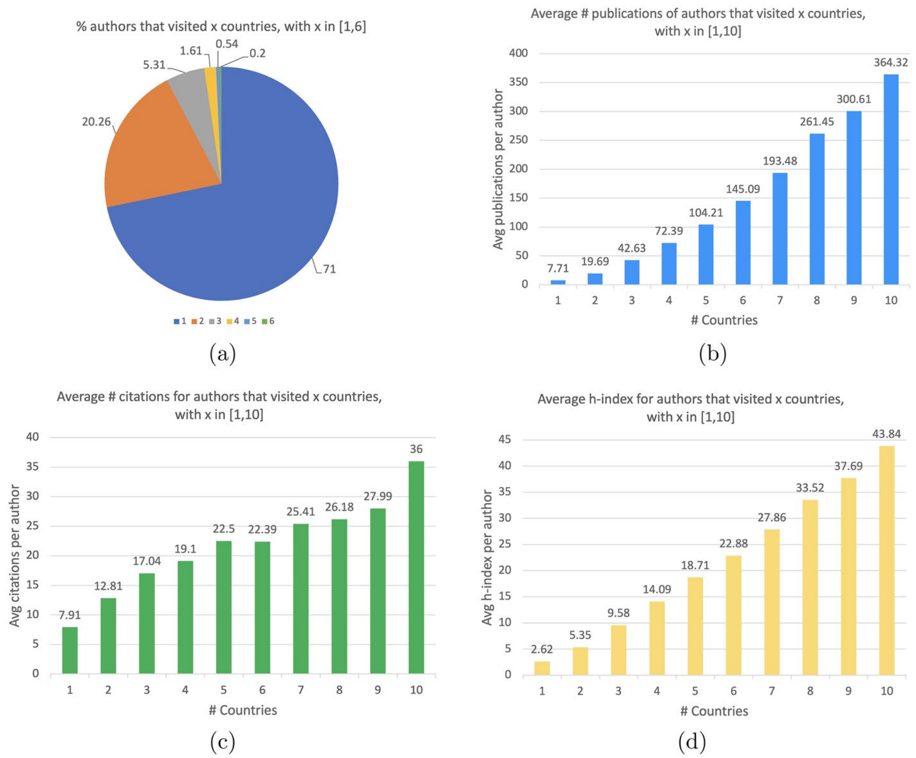

Fig. 1 CS authors in the time frame 1991–2020, grouped by number of distinct affiliation countries

In this section, we first investigate the extent to which CS authors are internationally mobile, and then whether there is a correlation between mobility and productivity/impact of their research. We first present an overall analysis for all CS authors active in the time frame 1991–2020 ("A bird's eye view on international mobility in CS" section), and then proceed to differentiate by academic seniority ("Academic seniority and mobility" section) and gender ("Gender and mobility" section).

A bird's eye view on international mobility in CS

To analyze the extent to which CS researchers are internationally mobile, we have clustered the authors active in the time frame 1991–2020 according to the number of distinct countries visited in that 30-year period, as obtained from the authors' affiliations. For each group, we have then computed the average number of author publications, average citations per publication, and average h-index, as measures of productivity and impact. We have discarded groups represented by less than 50 authors, that would not be statistically significant.

The results are reported in Fig. 1. As shown in Fig. 1a, in spite of our very restrictive definition of mobility that must be reflected in both affiliation and country changes, long-term international mobility is quite frequent: 29% of all CS authors had affiliations in at least two distinct countries. The other subfigures show that there is a strong positive correlation between the number of affiliated countries and all three selected bibliometric indicators (Pearson coefficient greater than 0.9 in all cases): the higher the number of visited countries, the higher the number of publications, citations, and h-index.

To help us understand how international mobility, and its relation with productivity, has evolved over time, Fig. 2 reports the same data as Fig. 1a and b, separately for three distinct decades (namely, 1991–2000, 2001–2010 and 2011–2020). We observe that, as we move towards the present, the percentage of authors with a single affiliation country in the relevant time frame increases, while long-term international mobility, as we have defined it, becomes proportionally less frequent. This behavioral change may be due to constantly increasing travel and remote connectivity opportunities that could make long-term relocations abroad progressively less and less necessary for international collaboration. Concerning productivity, the average number of publications per author remains strongly correlated with the number of distinct affiliation countries for all time periods considered, but it also significantly increases as we consider more recent decades. These results are in line with those reported in Demetrescu et al. (2022), which depict a fast-growing CS community, both in terms of number of researchers and publications, over the time period 1991–2020.

Since it is likely that more countries are visited by more senior authors, and also gender might affect mobility, in the following, we turn our attention to academic seniority and gender, trying to shed light on their impact on the correlation highlighted above.

Academic seniority and mobility

It is conceivable that more mature researchers might have more opportunities to be offered a position abroad, or that accumulating a number of distinct affiliation countries simply takes time. Both hypotheses imply that senior researchers should be more internationally mobile than junior ones. On the contrary, it might be conjectured that a large part of long-term affiliation changes take place at an earlier career stage, which should lead to only modest increases in the percentage of mobile researchers as their career progresses. In order to shed light on these aspects, Fig. 3 reports community size and bibliometric indicators for CS authors in the time period 1991–2020, grouped not only by number of distinct affiliation countries, but also by specific academic age ranges.

It can be seen from Fig. 3a that the percentage of sedentary authors significantly decreases at each seniority level (decreasing histogram bar heights for 1-country authors), while the percentage of mobile authors for each specific number of affiliation countries ≥ 2 typically increases from one academic age range to the next. Overall, the data suggest a community where international mobility happens at all seniority levels. Notably, the only near-exception is the percentage of 2-country researchers, that remains essentially constant at roughly 30% for the most senior authors (academic age > 25): this suggests that researchers who choose to move internationally only once, tend to do so before reaching the highest seniority level.

Regarding productivity and impact metrics, Fig. 3b to d shows that higher seniority is paired with higher average productivity: histogram bars are mainly increasing within each group. There are some outliers for young k-country authors, with $k \geq 6$ and academic age ≤ 7, and with $k = 8$ and academic age in (7, 12]: these exceptions are due to the fact that the number of such authors is very small (< 50), and results are not statistically significant. Within each academic age group, a strong correlation remains between the number of visited countries and bibliometric indicators (Pearson coefficient above 0.9 in all cases), mirroring what was observed for the overall data not grouped by academic seniority (see

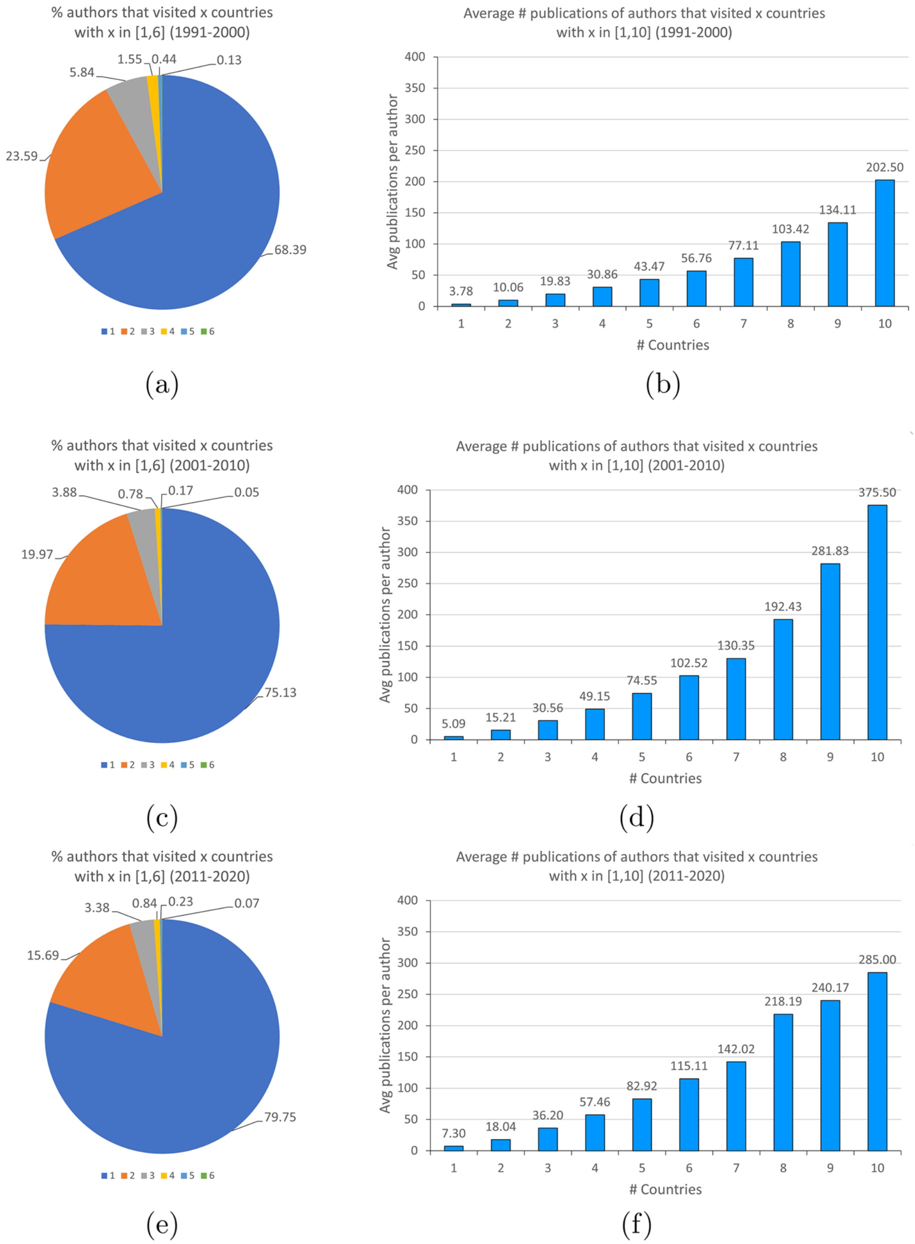

Fig. 2 CS authors and their average number of publications in the three decades 1991–2000 (**a**, **b**), 2001–2010 (**c**, **d**), 2011–2020 (**e**, **f**), grouped by the number of distinct affiliation countries

Fig. 1). A similarity can also be observed, in terms of bibliometric indicators, between the more mobile researchers of an academic age group and the less mobile of the next: e.g., the number of publications of 6-country authors with academic age in (12, 25] is very close to the number of publications of 5-country authors with academic age > 25. These

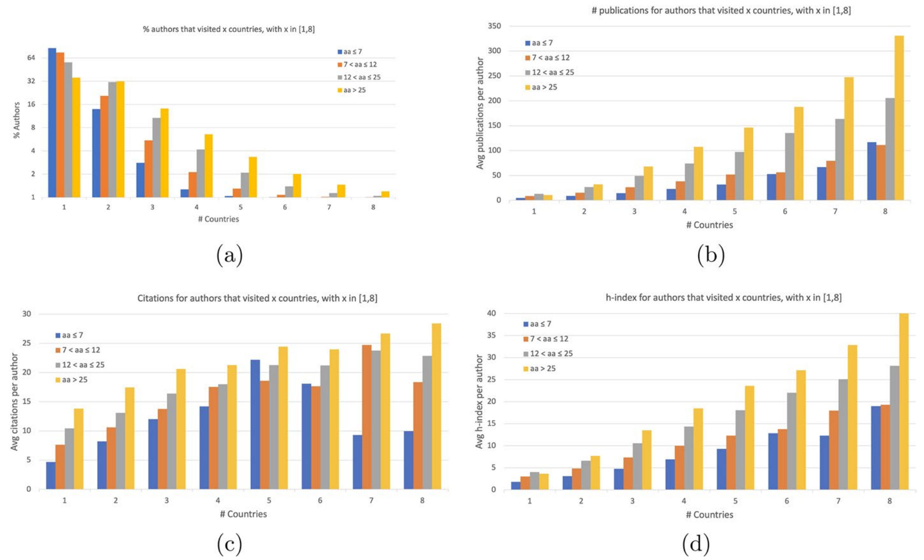

Fig. 3 Number of authors (**a**), publications (**b**), citations (**c**), and h-index (**d**) for CS authors with different levels of seniority, grouped by number of distinct affiliation countries: we report $aa \leq 7$, $7 < aa \leq 12$, $12 < aa \leq 25$, and $aa > 25$. Percentages in (**a**) are computed, for each aa range, w.r.t. all authors with seniority in that range

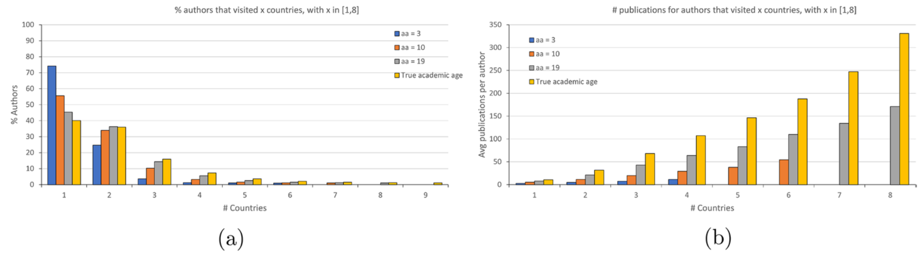

Fig. 4 Percentage of authors, and average number of publications per author, for CS authors at the highest level of seniority, computed on publication subsets tailored to generate statistics relative to earlier periods in their career: we report data for $aa = 3$, $aa = 10$, $aa = 19$, and their true aa

considerations provide evidence towards the conclusion that increasing academic seniority, while being a factor, is not the only cause for the observed correlation between productivity and number of visited countries.

As observed in "Extracting mobility and productivity data" section, all academic ages are computed with respect to the year 2020. This implies that, when analyzing different seniority levels, one is in fact comparing authors who started their career in different time periods. We now report the results of a complementary experiment in which, for each author with academic age > 25, only specific subsets of their publications are taken into account, effectively producing statistics relative to earlier periods of their career. In particular, we restricted publication sets so as to simulate academic ages 3, 10 and 19 (middle values in the academic age ranges used above). Figure 4 presents our results relative to the percentage composition and level of productivity of the various age groups per number of

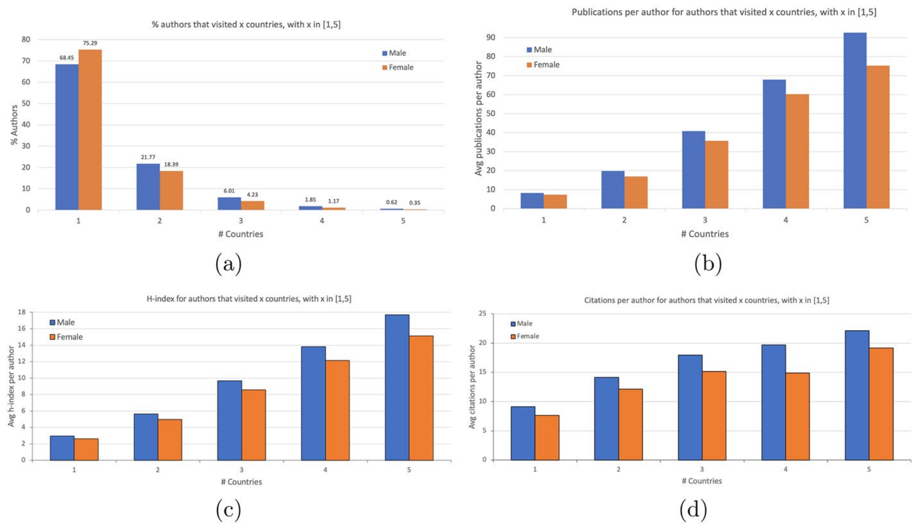

Fig. 5 Computer science female and male researchers in the time frame 1991–2020, grouped by number of distinct affiliation countries

distinct affiliation countries. A comparison with Fig. 3a and b reveals analogous trends, suggesting that both propensity to international relocation and scientific productivity, when expressed as functions of academic age, follow stable patterns throughout the period of observation.

Gender and mobility

Figure 5 plots the size of the community and the bibliometric indicators, separately, for male and female researchers, grouped by the number of countries of distinct affiliation in the period 1991–2020. A lower propensity of female researchers to move internationally in the long term, compared to their male colleagues, is evident from Fig. 5a: the percentage of females with a single associated affiliation country is 75.29%, while for males it is 68.45% (see Fig. 5a, 1-country authors). At the same time, all the other percentages (i.e., researchers affiliated with more than one country) are consistently lower for female authors compared to male authors. This supports the conclusion that women tend to be more stationary.

Focusing on scientific productivity, for each mobility group, the bibliometric indicators of male authors are higher than those of their female counterparts, and the gap seems to increase with the number of countries of affiliation (Fig. 5b–d). In order to shed light on the above aspects, we have investigated how productivity for different genders evolves also with academic age. The numerical results of our investigation for different academic ages are reported in Tables 1, 2, 3, and 4, respectively, as a function of the number of affiliation countries and gender. Similarly to the observations in "Academic seniority and mobility" section on the entire population, mobility seems to occur at all academic ages for both male and female researchers. However, women are less internationally mobile at all seniority levels: even at the earliest career stage, 1-country female researchers are 87.1%, as opposed to 82.9% for 1-country male researchers. In general, women of all academic ages

Table 1 CS authors with $aa \leq 7$ in the time frame 1991–2020, grouped by number of distinct affiliation countries and gender

Countries	Authors	% Authors	Publications	Citations	H-index	Gender
1	25,265	87.15	5.09	4.31	1.87	Female
2	3278	11.31	8.18	5.93	2.79	Female
3	380	1.31	12.52	7.12	4.08	Female
1	138,220	82.91	5.51	5.24	2.09	Male
2	24,157	14.49	9.23	8.63	3.28	Male
3	3610	2.17	14.66	11.84	4.86	Male
4	566	0.34	22.73	13.28	6.84	Male
5	90	0.05	31.82	17.41	8.88	Male

Table 2 CS authors with $7 < aa \leq 12$ in the time frame 1991–2020, grouped by number of distinct affiliation countries and gender

Countries	Authors	% Authors	Publications	Citations	H-index	Gender
1	11,376	74.68	8.32	7.37	3.05	Female
2	3011	19.77	14.05	9.18	4.50	Female
3	637	4.18	22.44	10.42	6.20	Female
4	144	0.95	34.54	11.91	8.92	Female
5	54	0.35	35.09	15.06	9.11	Female
1	86,422	72.79	8.65	8.73	3.21	Male
2	24,254	20.43	15.58	11.48	5.01	Male
3	5966	5.02	25.85	14.31	7.39	Male
4	1527	1.29	36.36	17.69	9.84	Male
5	404	0.34	48.72	19.29	11.68	Male
6	119	0.10	53.69	14.27	12.52	Male

Table 3 CS authors with $12 < aa \leq 25$ in the time frame 1991–2020, grouped by number of distinct affiliation countries and gender

Countries	Authors	% Authors	Publications	Citations	H-index	Gender
1	8578	58.54	12.13	11.36	4.13	Female
2	4232	28.88	23.33	13.88	6.42	Female
3	1282	8.75	41.75	15.25	9.83	Female
4	388	2.65	61.81	14.22	12.51	Female
5	115	0.78	81.12	19.77	16.29	Female
1	71,498	54.76	12.60	11.76	4.19	Male
2	39,099	29.95	25.77	14.58	6.86	Male
3	13,092	10.03	46.95	17.55	10.73	Male
4	4427	3.39	70.36	18.87	14.23	Male
5	1521	1.17	88.21	21.45	17.38	Male
6	588	0.45	123.11	21.49	20.99	Male
7	211	0.16	157.73	22.11	24.14	Male
8	66	0.05	172.82	25.26	26.70	Male

Table 4 CS authors with $aa > 25$ in the time frame 1991–2020, grouped by number of distinct affiliation countries and gender

Countries	Authors	% Authors	Publications	Citations	H-index	Gender
1	1098	41.58	10.98	13.37	3.86	Female
2	792	29.99	30.64	17.09	7.89	Female
3	303	11.47	67.29	20.08	13.97	Female
4	136	5.15	98.12	17.61	16.89	Female
1	13,095	36.62	10.79	15.10	3.75	Male
2	10,829	30.29	31.17	19.38	7.90	Male
3	4463	12.48	64.03	21.94	13.45	Male
4	1831	5.12	102.09	22.07	18.29	Male
5	767	2.15	131.63	23.69	22.45	Male
6	317	0.89	177.25	25.14	26.37	Male
7	131	0.37	215.91	30.42	32.67	Male
8	56	0.16	304.59	25.63	36.93	Male

are affiliated with fewer countries than their male counterparts: in each table, the number of rows for women is always less than the number of rows for men. This confirms what is shown in Fig. 5a, which is independent of the seniority level. Also, note that the percentage of stationary women decreases with academic age, and this is in line with the trend observed in Fig. 3a throughout the population.

It is worth noticing that bibliometric indicators for female authors tend to be lower than for male authors in all academic age groups but the last one (academic age larger than 25 in Table 4): here a substantial tie is achieved, with sometimes male, sometimes female researchers being ahead. We hypothesize that this may be due to a higher propensity of women, with respect to men, to adjust their career pace to deal more effectively with the encumbrances of family life. Remarkably, however, the initial gap seems to be finally closed upon reaching the highest level of seniority.

International career paths

Regarding international mobility, the *career path* of a researcher can be regarded as a time-ordered sequence of nodes, each representing a maximal period of years with with a consistent affiliation country (or countries, in the case of multiple affiliations). As an example, if an author started their career in China in 2001, then had a double affiliation in China and the United States in 2006, moved permanently to the United States in 2007, and came back to China in 2015, their career path would be:

$$China\ [2001--2005] \longrightarrow \{China, USA\}\ [2006]$$
$$\longrightarrow USA\ [2007-2014] \longrightarrow China\ [2015--2020]$$

We observed in our data that career paths exhibit quite a large variability, as they reflect each researcher's individual career choices.

The aim of this section is to understand whether general trends and patterns can be identified. In more detail, "Mobility graph analysis" section introduces and analyzes a mobility

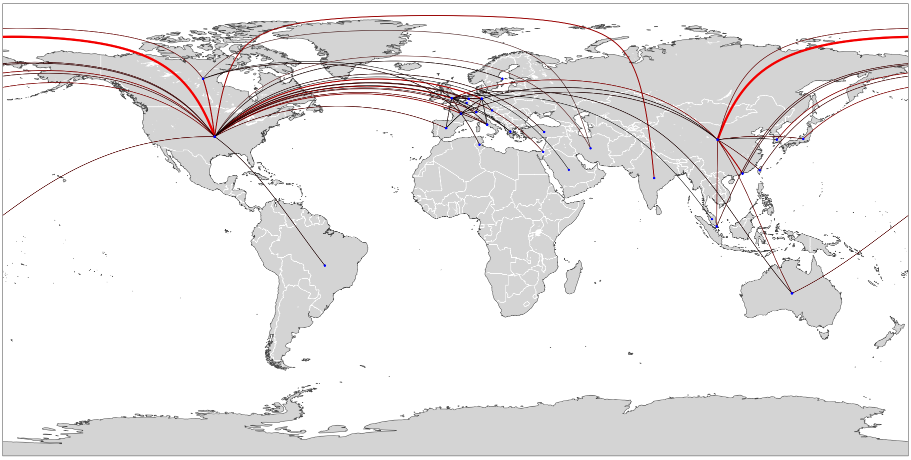

Fig. 6 Mobility graph obtained from the authors' career paths, restricted to edges with weight ≥ 750. Thicker and lighter edges are the most traversed, whereas thinner and darker edges are the least traversed

graph induced by the superposition of all career paths, identifying the most traveled connections between different countries, whether they are equally traversed in both directions, and what the country of origin (i.e., the country associated with the first affiliation) of each traveler is. "Time evolution of the mobility graph" section discusses how the mobility graph has evolved over time. "An analysis of mobility from G20 countries" section analyzes by country of origin the career paths of authors who started their career in any of the nations belonging to the G20 group, highlighting the most commonly visited foreign countries as well as the most frequent end-of-path countries (that is, those associated with the last affiliation). "Mobility behavior of top scientists" section takes a closer look at the patterns emerging from career paths of top scientists, comparing their international mobility to the overall population.

Mobility graph analysis

Information contained in individual career paths naturally induces a *mobility graph*, where each node represents a country and each (directed) edge represents an affiliation change from the country at its tail to the one at its head. We can also weight each edge according to the total number of times any author has traversed that edge. In the case of multiple-affiliation source and/or destination nodes in a career path, when building the graph, we took the cross-product between source country set and destination country set (excluding self-loops). As an example, if a career path contains an affiliation change:

$$\{China,\ USA\} \longrightarrow \{Italy,\ USA\}$$

this would add one to the weights of the directed graph edges (*China*, *Italy*), (*China*, *USA*), (*USA*, *Italy*). Notice that (*USA*, *USA*) is omitted being a self loop.

Figure 6 provides a graphical representation of the mobility graph, restricted to edges with weight ≥ 750 in order to declutter the visualization. Notice that, again for ease of visualization, lines are nondirectional and show the largest number of moves in either direction. In almost all cases, the difference between moves in one direction and the opposite one is quite low (below 30%). The only notable exceptions are the connections between Iran on one side and the US or Canada on the other. In these cases, the number of moves from Iran is much larger (2 to 3 times) than the number of moves towards Iran.

Table 5 also lists the heaviest edges in the mobility graph. For each edge, in addition to the overall number of traversals (i.e., the edge weight), Table 5 also reports the total number of distinct authors that traveled through that edge. This number is always smaller than the edge weight, because some authors move through the same edge more than once.

The most traveled edges are by far those between the US and China, in both directions. These are followed, not so closely, by edges from Canada to the US and from Hong Kong to China. The US are an important research hub: they also have a fairly tight relationship with the UK, Germany, and India, and to a lesser extent with France, South Korea, Japan, Italy, Switzerland, Israel, and Australia. China has significant exchanges with the UK, Singapore, Canada, Australia, and Japan. Germany and the UK also appear to have a solid connection.

It should be noted that the difference in weight between an edge and the one in the opposite direction is never too large, suggesting two-way exchanges, or possibly authors relocating to a foreign country, but going back home at a certain point in their career. Table 5 helps us investigate this phenomenon by reporting, for the heaviest edges in the mobility graph, a breakdown of the authors that traveled through those edges by country of origin (i.e., by the country associated with the author's affiliation in the first Scopus-indexed publication). For instance, let us focus on graph edge (*China*, *USA*), that has been traversed 11,829 times by 9,363 authors. Among these authors, 77% have their first affiliation in China, and China turns out to be the most frequent origin of authors traversing this edge. We notice that the country of origin (i.e., the first-affiliation country as reported in the first Scopus-indexed publication of a given author) may be different from the edge source node. In our example, 16% and 1% of the authors traversing edge (*China*, *USA*) have indeed their first affiliation in the United States and Hong Kong, respectively. For all the edges listed in Table 5, the vast majority of authors that move through them have one of the two edge endpoints as country of origin.

When comparing each edge with its reverse, we notice that in some cases the majority of authors in both directions have the same country of origin, suggesting a propensity of authors from that country to move back and forth along those edges, rather than a mutual exchange of researchers. For example, the majority of authors who move between China and the US have China as the first affiliation country, in both directions. The same holds for authors that move between China and several other countries, including Hong Kong, the UK, Singapore, Canada, and Australia. The percentage of authors with Chinese first affiliation that go back to China is always smaller than the percentage in the opposite direction, suggesting that some Chinese authors relocated abroad. Conversely, when examining the most traveled edges that connect the United States with other countries, we find that in several cases those edges are mostly populated by non-US authors: this is the case for Germany, France, Japan, Italy, Israel, and Spain.

For other edges, the data seem instead to suggest mutual exchanges: take, for instance, the United States and Canada, where authors moving from the US to Canada have the US as most frequent origin country, while authors moving from Canada to the US have Canada as most frequent origin country. This happens also for the connections between the US and the UK, India, South Korea, Switzerland, Australia, and Taiwan. Other cases of mutual exchanges involve Germany with the UK and China with Japan. We remark, however, that in some cases a significant percentage of authors with first affiliation in the

Table 5 Breakdown by first-affiliation country of authors travelling through the heaviest edges (and their inverses) in the mobility graph

Graph edge	Authors	Moves	1st most frequent origin, % authors	2nd most frequent origin, % authors	3rd most frequent origin, % authors
China → USA	9363	11,829	China, 77.67	USA, 16.03	Hong Kong, 1.42
USA → China	7796	10,009	China, 54.39	USA, 36.61	Hong Kong, 2.00
Canada → USA	4190	5405	Canada, 61.50	USA, 20.62	China, 2.72
USA → Canada	3232	4191	USA, 50.56	Canada, 30.57	China, 2.72
China → Hong Kong	3170	4302	China, 73.79	Hong Kong, 17.38	USA, 3.41
Hong Kong → China	3420	4914	China, 47.43	Hong Kong, 43.22	USA, 3.39
UK → USA	4070	5077	UK, 46.51	USA, 28.30	Germany, 3.10
USA → UK	3872	4822	USA, 50.62	UK, 23.81	Germany, 3.31
Germany → USA	3939	5021	Germany, 65.40	USA, 19.45	France, 1.42
USA → Germany	3490	4322	Germany, 42.55	USA, 39.97	Switzerland, 1.83
India → USA	3906	4574	India, 68.97	USA, 25.65	Canada, 0.69
USA → India	2904	3582	USA, 65.39	India, 27.24	Canada, 1.24
France → USA	2746	3459	France, 63.73	USA, 17.59	Germany, 2.22
USA → France	2351	2911	France, 43.90	USA, 35.69	Italy, 2.98
South Korea → USA	2378	2903	South Korea, 72.04	USA, 21.99	China, 0.76
USA → South Korea	2665	3487	USA, 57.30	South Korea, 37.15	China, 1.05
China → UK	2151	2723	China, 72.48	UK, 15.76	USA, 2.05
UK → China	2211	2881	China, 47.63	UK, 38.63	USA, 2.44
Japan → USA	2501	2976	Japan, 65.89	USA, 21.55	China, 2.24
USA → Japan	2285	2668	Japan, 51.12	USA, 37.37	China, 1.79
China → Singapore	1676	2148	China, 76.13	Singapore, 14.38	USA, 2.63
Singapore → China	1734	2358	China, 48.50	Singapore, 38.52	Hong Kong, 3.40
Italy → USA	1843	2441	Italy, 74.06	USA, 15.14	UK, 1.52
USA → Italy	1367	1734	Italy, 57.79	USA, 30.21	UK, 1.39
Canada → China	1568	2035	China, 60.46	Canada, 28.32	USA, 3.25
China → Canada	1792	2268	China, 80.52	Canada, 10.44	USA, 2.79
Australia → China	1464	1894	China, 57.72	Australia, 28.76	Hong Kong, 2.46
China → Australia	1693	2174	China, 78.38	Australia, 11.70	USA, 2.19
Germany → UK	1713	2159	Germany, 64.39	UK, 13.72	USA, 3.97
UK → Germany	1478	1834	UK, 39.51	Germany, 39.04	USA, 3.38
China → Japan	1276	1588	China, 65.60	Japan, 26.96	USA, 2.35
Japan → China	1537	2064	Japan, 56.99	China, 35.20	USA, 2.73
Switzerland → USA	1544	2037	Switzerland, 47.02	USA, 23.77	Germany, 6.67
USA → Switzerland	1393	1821	USA, 45.80	Switzerland, 22.83	Germany, 7.11
Israel → USA	1405	2061	Israel, 75.30	USA, 18.01	India, 0.71
USA → Israel	1129	1643	Israel, 56.60	USA, 35.52	Canada, 1.15
Australia → USA	1496	1853	Australia, 49.67	USA, 26.00	China, 4.41
USA → Australia	1385	1713	USA, 47.87	Australia, 28.01	China, 3.10
Spain → USA	1471	1867	Spain, 67.64	USA, 14.75	Italy, 2.58
USA → Spain	1259	1556	Spain, 51.31	USA, 30.18	UK, 2.14
China → Taiwan	1276	1461	Taiwan, 58.86	China, 29.94	USA, 7.45
Taiwan → China	1498	1773	Taiwan, 75.43	China, 13.75	USA, 6.88
Taiwan → USA	1120	1371	Taiwan, 70.80	USA, 25.09	China, 1.25

Table 5 (continued)

Graph edge	Authors	Moves	1st most frequent origin, % authors	2nd most frequent origin, % authors	3rd most frequent origin, % authors
USA → Taiwan	1290	1648	USA, 67.21	Taiwan, 29.07	China, 1.09

US and relocating to a different country may be foreign students returning home: a recent survey (NCSES, NSF, 2022), for instance, lists India, South Korea, Taiwan, and Canada among the nations with the largest numbers of recipients of US PhD's in science and engineering over the time period 2011–2021.

Figure 7 provides a graphical representation of the mobility graph, restricted to the EMEA (Europe, Middle East and Africa) area, including edges with weight ≥ 90 in order to include more connections. Analogously to the previous figure, lines are non-directional as, in most cases, moves in one direction and in the opposite one are of the same order of magnitude. There are two exceptions worth mentioning. First, as already observed in Fig. 6, Iran has many more CS researchers leaving than moving in. Second, Saudi Arabia appears to be attracting far more researchers than those that leave the country. This is probably due to the fact that Saudi Arabia invested massively in the field recently and has attracted a significant number of researchers. Due to the recent start of this policy, most of these researchers are still in the country.

We notice that there are several destinations in Europe that attract international researchers (France from North Africa, UK and Germany from the Middle East) as well as a quite significant exchange of researchers between many European countries (UK, Germany, France, Italy, Spain, Switzerland and others).

Time evolution of the mobility graph

In order to assess how the mobility graph has evolved over time, edge weights have been recomputed separately, based on publications from each of three consecutive decades (namely, 1991–2000, 2001–2010 and 2011–2020). We have selected the top-20 heaviest edges in each decade: this resulted in 28 distinct mobility edges listed in Table 6. For each of these edges, we have considered its rank in each selected time frame. The ranks are reported in Table 6 and a graphical representation is provided in Fig. 8, showing a tripartite graph with one column per decade: nodes of this graph correspond to mobility edges, are duplicated in each decade, and are connected by an arc if their label is the same. The steepest arcs correspond to the largest rank changes, and are green or red when a rank increases or decreases substantially from one decade to the following one.

It is interesting to note that the edges that have undergone the largest increments in their ranking almost invariably contain China as one of their endpoints. This is the case, for example, of (*China*, *USA*), whose rank evolution from the most distant to the most recent decade is (20, 1, 1), or its reverse, (*USA*, *China*), whose rank evolution is (21, 2, 2). These rank variations clearly indicate that the (bidirectional) connection between the US and China had already become the most prominent in the world in the 2001–2010 decade, and it has managed to retain its primacy through the most recent decade as well. The bidirectional connections between China and Hong Kong and China and the UK have also seen significant improvements in their prominence over the studied decades. And so have the connection from Singapore to China (evolutionary pattern (167, 32, 16)) and from China to Australia (pattern (215, 48, 18)).

Fig. 7 Focus on EMEA (Europe, Middle East and Africa) of the mobility graph obtained from the authors' career paths, restricted to edges with weight ≥ 90. Thicker and lighter edges are the most traversed, whereas thinner and darker edges are the least traversed

Another interesting case is the relationship between the US and India. The connection from India to the US has seen a significant increase in relevance, especially in the most recent decade, as proven by its rank evolution: (18, 15, 4). This, however, has not been paralleled by a comparable rank improvement of the opposite connection (i.e., from the US to India), which exhibits the evolutionary pattern (17, 17, 13).

The rank improvements reported above have come at the expense of more "traditional" connections progressively losing ground in an increasingly globalized landscape. These include, most notably, the connection from Canada to the US (evolutionary pattern (1, 3, 7)) and its reverse (pattern (2, 4, 12)), which had started as the busiest connections in the world in the 1991–2000 decade. Other connections that have lost significant ground over the studied decades include those between the US and Japan and

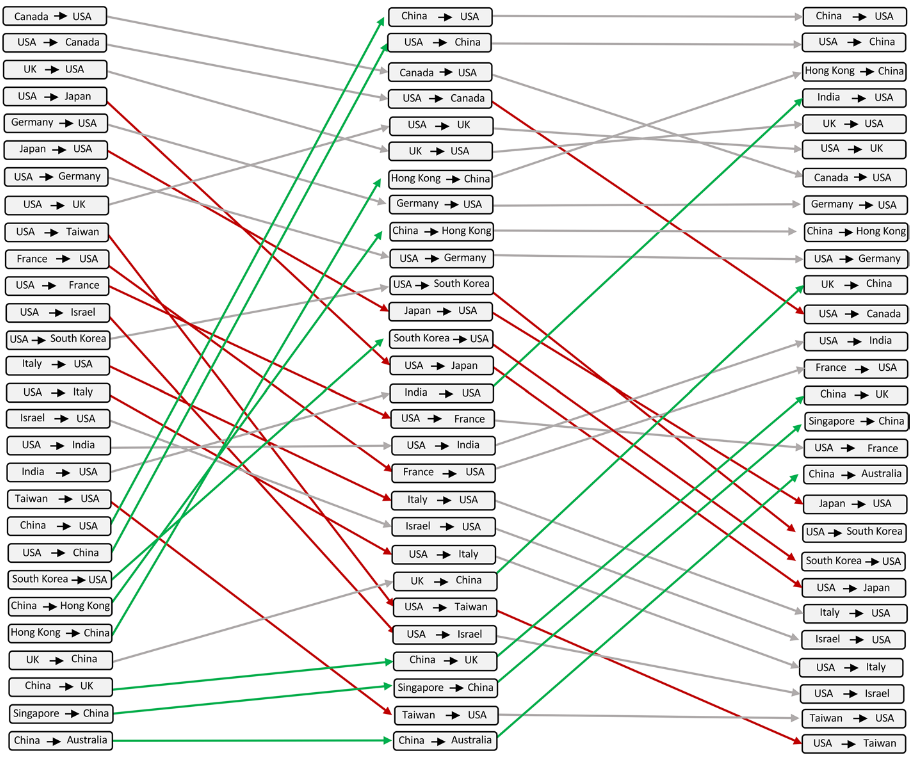

Fig. 8 Tripartite graph representing the rank evolution of the heaviest edges in the mobility graph. Nodes in the left, middle and right columns are sorted according to their ranks in the time periods 1991–2000, 2001–2010 and 2011–2020, respectively. Arcs marking substantial rank increases from one decade to the next are colored in green, while arcs marking significant rank decreases are colored in red. (Color figure online)

the US and Taiwan (bidirectional in both cases), and those from the US to Italy and to Israel.

An analysis of mobility from G20 countries

In this section we analyze the characteristics of international mobility starting from the 19 countries of the G20 group (we consider the full Group of Twenty, except for the European Union). After partitioning G20 authors into 19 clusters, based on their first affiliation country, we have calculated the most visited foreign countries by authors in each cluster. Table 7 summarizes the result of this analysis, showing the four topmost visited foreign countries in decreasing order of frequency, that is, decreasing percentage of authors who visited that country. We assume that an author has visited a country c if c appears in their career path at least once, even if only in multiple-affiliation nodes. We remark that the use of percentages in Table 7, in contrast to the absolute values reported in Table 5, provides an alternative view where the proportional strength of the connection between countries is emphasized, regardless of the absolute size of their CS communities.

The third column in Table 7 shows that, for all countries but Indonesia, the US are the most commonly visited nation, confirming their attractiveness for researchers in the

Table 6 Ranks by decade of top-20 (in at least one decade) mobility graph edges

Graph edge	Edge rank (1991–2000)	Edge rank (2001–2010)	Edge rank (2011–2020)
China → USA	20	1	1
USA → China	21	2	2
Hong Kong → China	46	7	3
India → USA	18	15	4
UK → USA	3	6	5
USA → UK	8	5	6
Canada → USA	1	3	7
Germany → USA	5	8	8
China → Hong Kong	42	9	9
USA → Germany	7	10	10
UK → China	137	25	11
USA → Canada	2	4	12
USA → India	17	17	13
France → USA	10	18	14
China → UK	155	30	15
Singapore → China	167	32	16
USA → France	11	16	17
China → Australia	215	48	18
Japan → USA	6	12	19
USA → South Korea	13	11	20
South Korea → USA	22	13	21
USA → Japan	4	14	24
Italy → USA	14	19	28
Israel → USA	16	20	33
USA → Italy	15	24	38
USA → Israel	12	27	43
Taiwan → USA	19	45	56
USA → Taiwan	9	26	75

Rows are sorted according to rank in the 2011–2020 time period

field of CS, as already outlined in "Mobility graph analysis" section. The second most visited country is often either the United Kingdom or China. China is also the most commonly visited country for authors who started their careers in the US. It seems plausible, however, that a non-negligible percentage of these authors are Chinese students going back to their native country after a career start in the US: the NCSES, NSF (2022) survey reports as many as 54,645 Chinese recipients of a PhD in the US for science and engineering over the time period 2011–2021. Other countries visited with relative frequency appear to reflect linguistic or cultural heritage. This is the case, for example, of Spain, the second most visited nation by researchers with Argentina or Mexico as their country of origin. Chinese authors have Hong Kong as their second most visited country. Other noteworthy examples include Portugal, which appears among the most visited countries by authors who started their career in Brazil, Egypt for authors who started in Saudi Arabia and Cyprus for those who started in Turkey.

Table 7 Most commonly visited foreign countries by authors that started their career in a nation belonging to the G20 group

Country of origin	Mobile authors	% total authors	1st visited,% mobile authors	2nd visited,% mobile authors	3rd visited,% mobile authors	4th visited,% mobile authors
Argentina	342	22.56	USA, 24.85	Spain, 23.39	France, 16.08	Germany, 6.43
Australia	3312	27.59	USA, 25.00	China, 14.67	UK, 13.04	Germany, 5.04
Brazil	2541	16.31	USA, 28.02	France, 14.95	UK, 10.70	Portugal, 10.11
Canada	5383	31.68	USA, 51.42	China, 10.27	UK, 6.95	France, 6.58
China	18,045	8.47	USA, 41.61	Hong Kong, 13.22	UK, 9.23	Canada, 8.30
France	8586	31.07	USA, 23.33	UK, 10.63	Germany, 8.42	Canada, 7.87
Germany	8580	19.81	USA, 33.67	UK, 14.64	Switzerland, 10.07	France, 7.30
India	5975	8.06	USA, 47.23	UK, 6.68	Singapore, 6.01	Canada, 5.57
Indonesia	608	6.72	Japan, 19.41	Malaysia, 13.49	Taiwan, 9.70	Australia, 9.05
Italy	5358	28.29	USA, 28.91	UK, 16.98	France, 15.10	Germany, 11.78
Japan	4900	12.36	USA, 35.41	China, 18.76	UK, 5.57	Germany, 5.08
Mexico	792	17.55	USA, 23.11	Spain, 21.84	France, 13.13	UK, 10.23
Russian Fed.	1159	7.73	USA, 29.59	Germany, 12.86	UK, 10.70	France, 7.33
Saudi Arabia	647	29.90	USA, 21.48	Canada, 14.22	UK, 13.45	Egypt, 8.04
South Africa	424	17.14	USA, 21.46	UK, 12.26	Nigeria, 8.49	Australia, 7.78
South Korea	3670	13.33	USA, 48.58	China, 10.90	Japan, 6.81	UK, 5.07
Turkey	1691	19.40	USA, 40.09	UK, 11.18	Germany, 7.81	Cyprus, 6.86
UK	9177	33.03	USA, 23.90	China, 10.45	Germany, 7.43	France, 4.98
USA	20,916	16.59	China, 14.80	UK, 10.64	India, 9.50	Canada, 8.40

In order to add a temporal perspective to our investigation about the most frequently visited foreign countries by G20 authors, we repeated our analysis separately for three distinct decades (namely, 1991–2000, 2001–2010 and 2011–2020). The obtained results are mostly in line with those referring to the full 1991–2020 time period. The preferred destination remains, for all decades, the US, starting from almost all other countries. For researchers whose origin country is the US, the most visited foreign nation remains China for the decades 2001–2010 and 2011–2020, while it was Taiwan for the time period 1991–2000. Popular destinations other than the US include the UK, China (starting from the 2001–2010 decade) and countries reflective of linguistic or cultural heritage (e.g., Spain for authors originating from Argentina or Mexico).

Mobility behavior of top scientists

In order to assess whether and how the characteristics of career paths vary with scientific productivity, in this section we focus on the top 1% (in terms of h-index) of researchers who started their career in each nation in the G20 group.

Table 8 reports the foreign countries that are the most visited by the top authors and can be directly compared with Table 7. The United States remain the most visited nation for almost all G20 countries. Interestingly, the percentages of top researchers who relocated to the US at least once are considerably higher than the values obtained for overall authors, suggesting an even more important role of this country as a central hub among prominent scientists.

When comparing data related to the overall authors' population and to the subset of top scientists, a general observation is that the percentage of internationally mobile authors is significantly higher among top researchers than among all authors. This is in line with the results in "Correlation between mobility and productivity" section, where we reported a strong correlation between international mobility and researchers' productivity.

Discussion

In "Correlation between mobility and productivity" section, we have seen that there is a strong correlation between the international mobility of computer science researchers and their scientific productivity and impact. This seems to be in line with a majority of previous works, although none of them focuses specifically on computer science. We highlight that the size of the datasets used in many previous works is significantly smaller than our study, which spans a time period of 30 years and involves a total of 969,835 researchers and 8,412,543 publications.

Taking for granted the correlation between mobility and bibliometric indicators for CS, it would be interesting to understand whether there is a causal relation between the two. Does mobility cause productivity to increase? Or is there a positive selection effect, whereby mobile authors are above average since the very beginning, i.e., even before they relocate abroad? At this aim, one should be able to analyze not just the overall productivity of an author, but also its evolution over time, in order to understand if the author became more productive after relocating. This is a very fine-grained level of granularity that the aggregated datasets we extracted from Scopus do not currently support. We plan to tackle these issues in future work.

Table 8 For each nation in the G20 group, most commonly visited foreign countries by the top 1% (in terms of h-index) internationally mobile authors who started their career in that nation

Country of origin	Mobile authors	% total authors	1st visited,% mobile authors	2nd visited,% mobile authors	3rd visited,% mobile authors	4th visited,% mobile authors
Argentina	12	80.00	USA, 41.67	UK, 33.33	Germany, 25.00	France, 16.67
Australia	113	96.58	China, 53.10	USA, 44.25	UK, 24.78	Hong Kong, 15.93
Brazil	111	71.61	USA, 50.45	Canada, 19.82	France, 16.22	Australia, 9.91
Canada	159	95.78	USA, 67.30	China, 33.33	UK, 19.50	Australia, 13.21
China	1,482	70.20	USA, 50.88	Hong Kong, 24.70	UK, 16.19	Australia, 13.36
France	232	85.61	USA, 50.86	UK, 24.57	Germany, 16.38	Canada, 14.66
Germany	379	88.97	USA, 59.37	UK, 27.70	Switzerland, 21.37	Canada, 11.35
India	459	62.28	USA, 54.03	UK, 13.29	Singapore, 13.07	Australia, 8.50
Indonesia	38	41.76	Japan, 31.58	Malaysia, 21.05	India, 13.16	Netherlands, 7.89
Italy	158	84.49	USA, 57.59	France, 20.89	UK, 20.89	Germany, 18.35
Japan	297	76.35	USA, 50.84	China, 31.99	UK, 15.15	Canada, 12.79
Mexico	33	73.33	USA, 48.48	Spain, 18.18	China, 12.12	France, 12.12
Russian Fed.	97	67.83	USA, 44.33	UK, 27.84	Germany, 18.56	Switzerland, 8.25
Saudi Arabia	21	95.45	USA, 38.10	Pakistan, 23.81	Egypt, 19.05	Canada, 14.29
South Africa	21	84.00	USA, 38.10	UK, 23.81	Australia, 19.05	Canada, 14.29
South Korea	208	76.47	USA, 64.42	China, 16.35	Canada, 10.10	Japan, 9.62
Turkey	58	66.67	USA, 60.34	UK, 22.41	Canada, 17.24	France, 10.34
UK	253	92.67	USA, 58.89	China, 26.88	Germany, 15.02	Australia, 12.65
USA	894	73.16	China, 31.32	UK, 19.57	Canada, 15.55	Germany, 13.87

The career paths analyzed in "International career paths" section reveal interesting patterns. Not surprisingly, the United States are a preferred destination for internationally mobile authors starting their career in one of the G20 countries, and this is even more so for top scientists. The United Kingdom is typically second, followed by China, Canada, and other European countries such as Germany and France. Overall, we observed from the data a marked tendency for mobile authors to return to their homeland at a certain point in their career, and the most common destination, when it does not coincide with the country of origin, is again the United States.

While the role of the US as a central hub for international mobility in the field of CS over the time period 1991–2020 can hardly be disputed, it seems instructive to briefly compare the results in this article with those reported in Demetrescu et al. (2022), where the time evolution of the CS community in the last thirty years has been analyzed. At the beginning of the observation period, the US represented by far the dominating country in terms of CS research, and while witnessing a constant erosion of its preeminence, managed to retain this leadership until very recently. However, in the last five years of the observation period (2016-2020), China—starting from a far way behind—has finally overtaken the US in terms of percentage of authors (over total world authors), number of publications, and world share of citations. The US remains the leading country for publication impact (i.e., average citations per publication). The predominant role in terms of impact is remarkably consistent with the fact that the US appears to be a central hub for international mobility, emphasizing once again the correlation between mobility and productivity. It also seems noteworthy that the runner-up nation, China, is, starting from the early 2000s, one of the most internationally connected, especially to the US themselves, according to our study. If the current trend continues, and China manages to fully replace the US as leading country in CS research, it will be interesting to monitor whether this also reflects in international mobility patterns, or if political or cultural barriers will hinder (or delay) such a process.

Concluding remarks and future research

In this paper, we have studied the long-term international mobility of computer science researchers over a period of thirty years, making two major contributions.

- We have shown that even the rather restrictive type of mobility we have analyzed is a frequent phenomenon in a very young discipline such as CS. As a first outcome of our study, mobility strongly correlates with research productivity, measured in terms of standard bibliometric indicators. Although increasing academic age plays a role in this correlation, we present strong evidence that it cannot be its only cause. We also observed a lower propensity of female researchers towards international mobility, compared to their male colleagues, for all academic ages, as well as lower productivity and impact at all mobility and seniority levels, except for the highest seniority ($aa > 25$) where a substantial tie is achieved.
- As a second contribution, we analyzed individual career paths and characterized a worldwide mobility graph, placing the United States as a central hub for international mobility in CS. With very few exceptions, it is by a considerable margin the preferred destination of researchers relocating abroad from other G20 countries, and even more so when considering top scientists. Other well-connected countries in our mobility

graph include the United Kingdom, China, Canada, Germany, and France. The connection between the US and China is the busiest in the world, in terms of the absolute number of researchers moving back and forth. It also seems noteworthy that the majority of these researchers have started their career in China.

Our work sheds light on important aspects of computer science research, but also leaves open many interesting research avenues. We highlight some of them below.

- While we detected a strong correlation between international mobility and research productivity, the question of whether there is a causal relation between the two remains open, as pointed out also in the discussion of "Discussion" section.
- Our focus on macro tendencies let us approach international mobility from a coarse-grained point of view, where only affiliation countries matter. A finer-grained approach, considering specific institutions and, if possible, their relative level of "prestige", could yield complementary insights and could pave the way for an analysis of domestic mobility (i.e., mobility within the same country).
- The central position of the US in computer science research and the recent rise of China need further investigation. It would be very interesting to understand if, besides academia, the presence of technology giants in the US and China had an impact on the development of the computer science community, by analyzing specific affiliations and trying to characterize industrial vs. academic research. Analyzing the mobility of researchers between academia and companies would be another interesting research direction.
- Understanding the sociological reasons behind the lower level of international mobility of women would be very interesting. While cultural heritage might partially explain this phenomenon, it is surprising that it happens also for young generations and since the very beginning of the career, when major differences are not expected.
- Our article focused on computer science as a case study, as this field is extremely dynamic and quite relevant to the present development of technology, but similar techniques could be applied to other research domains. In this respect, Scopus' own classification of research output into subject areas might serve as a useful starting point.

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Declarations

Conflicts of interest The authors have no conflicts of interest to declare.

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