Geant4 in Scientific Literature

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Abstract—The Geant4 reference paper published in Nuclear Instruments and Methods A in 2003 has become the most cited publication in the whole Nuclear Science and Technology category of Thomson-Reuters’ Journal Citation Reports. It is currently the second most cited article among the publications authored by two major research institutes, CERN and INFN. An overview of Geant4 presence (and absence) in scholarly literature is presented; the patterns of Geant4 citations are quantitatively examined and discussed.

I. INTRODUCTION

Previous studies [1] have highlighted that software-oriented publications are largely underrepresented in scholarly literature related to particle physics, with respect to hardware-oriented ones. Nevertheless, a relatively recent software paper, describing the Geant4 Monte Carlo system [2], has become the most cited publication in the Nuclear Science and Technology category defined by Journal Citations Reports [3].

Geant4 is an object oriented toolkit, which provides a wide set of tools for the simulation of particle interactions with matter. Its development started at the end of 1994 and was motivated by the requirements of the experiments at the LHC (Large Hadron Collider) at CERN; nevertheless, since its first release at the end of 1998, Geant4 has been used by a large community in a variety of multi-disciplinary experimental applications beyond its original scope.

Despite the wide popularity of this software system, there is limited quantitative documentation of its impact on the production of physics results, its contribution to technological developments, its role in high energy physics and the relative extension of its use in this field with respect to other domains.

This paper presents a quantitative analysis of citation patterns related to Geant4 reference publications [2, 4]. Through these data we illustrate the role played by Geant4 in experimental physics prior to LHC startup.

II. DATA SOURCES AND ANALYSIS METHOD

The main source of data for this study is Thomson-Reuters’ Web of Science [5]. The subscription to which the authors had access covers the period since 1990 to the present date. Together with publication data, the Web of Science includes a set of tools for searching the database and analyzing the search results. The citing papers were identified through the tools available in the Web of Science; the analysis was restricted to those published before 2009, to avoid evolutions of the primary data sample during the analysis process.

In the course of the analysis, Thomson-Reuters introduced some changes in the classification of papers in the Web of Science, concerning conference proceedings publications, which affected the results of various data selections. The configuration management applied in the analysis process ensured the reproducibility of consistent results in the course of the project, despite the changes in the database: the primary data sample of citations could be reproduced within approximately 1% throughout the duration of the study, and the outcome of its analysis remained consistent.

According to the latest version of the Thomson-Reuters’ database used for this study (on October 13, 2009), the selected data sample consisted of 1089 papers citing [2] and 127 papers citing [4].

Complementary analyses were based on publishers’ web interfaces providing full-text search capabilities: the American Physical Society (APS), Elsevier and IEEE.

Most of the analyses were performed through automated tools provided by the ISI Web of Science and the publishers; nevertheless, some of them, requiring more detailed appraisals than the information available through automated tools, involved a manual inspection of the publication records.

III. MONTE CARLO IN PHYSICS AND TECHNOLOGY LITERATURE

A preliminary analysis concerned the role played by Monte Carlo simulation in physics and technological literature pertinent to experimental particle and nuclear physics, and related research fields such as astronomy and medical physics.

A set of well known codes was considered for this purpose: EGS [6], [7], [8], FLUKA [9], [10], GEANT 3 [11] and Geant4 [2, 4], MCNP [12], [13], [14] and Penelope [15]. This selection is not meant to be exhaustive, rather representative of the field.

Not all these Monte Carlo systems can be associated with a reference publication in an archival journal: for some of them the references are institutes’ reports or contributions to conference proceedings. Therefore, this analysis was based on the mention of the codes in the literature, rather than the citation statistics of proper reference articles.

The results were collected by means of the full-text tools provided by a few major publishers in the field through their web interfaces. The search pattern identified the various versions of the codes and naming variants commonly mentioned in the scientific literature (e.g. MCNP and MCNPX, EGS version 4 and 5 etc.). Papers mentioning FLUKA were manually inspected to ascertain whether they concerned the
standalone FLUKA code or the FLUKA package interfaced to GEANT 3: in the latter case, they were associated with GEANT 3.

The journals examined in this analysis were the Physical Reviews (A, B, C, D, E and Letters) as representative of physics journals, IEEE Transactions on Nuclear Science (TNS) and Nuclear Instruments and Methods (NIM), both A and B, as representative of technology journals. Among the Physical Reviews, most of articles mentioning the Monte Carlo codes considered in this study are published in Physical Review Letters, Physical Review D and C (97% of them over the years from 1990 through 2008); therefore the analysis focused on these three journals.

One can observe in Figs. 1-3 that, as a general trend, the use of Monte Carlo codes has increased both in physics and technology journals.

Monte Carlo simulation enables the production of physics results and supports technological research. Out of the 13407 papers published by NIM and the 2630 ones published by TNS over the 2004-2008 period, respectively 45% and 58% mention “simulation” or “Monte Carlo” in the text. This pattern appears correlated with modeling: over the same period, 64% of the articles published in TNS mention “model” or “modeling”, out of which 44% also mention “simulation” or “Monte Carlo”.

The papers mentioning the considered Monte Carlo codes amount to 15% and 9% of those published respectively by TNS and NIM in 2004-2008; their distributions are shown in Fig. 5.

An evident result that emerges from this analysis is the
continuing wide use of GEANT 3 in recent years, despite the fact that the latest version of this code (3.21) dates back to 1994. The use of GEANT 3 is more extensive in physics journals over technology ones, and in NIM over TNS.

Various factors contribute to the continuing significant presence of GEANT 3 in fundamental physics journals. A large number of physics publications in APS journals derive from experiments that started taking data before Geant4 was first released, or shortly after its release, when this code was not established yet, and are still actively analyzing their data to produce physics results. Despite the more advanced features offered by Geant4 with respect to GEANT 3, moving to a new code would represent a major risk and effort for a mature experiment in the course of its physics analysis, and could affect the systematics of the results. For this reason, most of these experiments tend to maintain a consistent simulation production environment over their lifecycle, and still rely on the Monte Carlo system, GEANT 3, on which they initially based their simulations. The requirement for many experiments to keep their simulation environment unchanged throughout their lifecycle is confirmed by the fact that, among the papers published between 2004 and 2008, some mention older GEANT versions than the latest 3.21 release, extending down to version 3.13.

In other cases of more recent high energy and nuclear physics experiments, the use of GEANT 3 is motivated by the decision of pursuing the experimental activity in a procedural programming environment, thus avoiding the transition to the object oriented technology associated with Geant4, which is perceived as a demanding investment of resources.

The type of research within the scope of technology journals is more likely to profit from the new functionality and modern software technology offered by Geant4; in this respect, TNS appears more open than NIM towards the use of Geant4 over GEANT 3.

With the exception to some extent of MCNP, which is relatively often mentioned in Physical Review C, GEANT 3 and Geant4 jointly are by far the most widely used simulation environment in fundamental particle and nuclear physics experiments, by far outstripping EGS, FLUKA and Penelope. Among technology journals, MCNP plays a significant role jointly with Geant4 and GEANT 3.

IV. GEANT4 CITATION PATTERNS

The distribution of Geant4 citations since the publication of [2] is shown in Fig. 6. One observes a growing trend as a function of time, that seems to be slower in recent years; however, this effect should be verified over a more extended time scale, and could be affected by major events in experimental research, such as the start of LHC operation foreseen at the end of 2009. Currently, [2] averages approximately a citation per day.

A striking feature of Fig. 6 is the much smaller number of citations collected by [4] with respect to [2], despite the fact that both publications are indicated on the Geant4 web page as references for the code. Nevertheless, citations to [4] contribute approximately 10% to the 2006 portion of TNS 2008 impact factor. The correct citation of this reference at the same level as [2] would have contributed to raise the journal’s impact factor considerably in 2007 and 2008.

Due to the limited statistical significance of the citation sample associated with [4], the analysis of citation patterns has been focused on [2]. The results related to [4] confirmed in general the citations patterns observed with [2]; the few relative differences are discussed in the following sections.

Reference [2] is the second most cited paper for CERN and INFN (over the period covered by the ISI Web of Knowledge accessible to the authors); it was ranked fourth relative to both institutes at the time of publication of [1].

A large fraction (approximately 17%) of the citations to [2] derive from a single high energy physics experiment, BaBar [16], located at Stanford Linear Accelerator Center; this feature could affect the overall appraisal of the citation patterns. Some of the analyses have been performed not only on the whole citation data sample, but also on a subset excluding BaBar contributions, to evaluate the possible bias introduced by the large weight of this experiment in the overall picture.

A. Geographical distribution

The distributions of citations to [2] by geographical area and country are shown in Tables I and II. The latter is limited to the countries ranked in the top 10 positions in terms of number of citations; the equivalent distribution excluding BaBar papers is in Table III. The totals in these tables and in the following ones (IV, VI) are larger than 100%, since the co-authors of a paper may come from multiple geographical areas, countries and institutes.

The largest number of citations come from Europe as a geographical area and from the United States as an individual country. The role of the USA as the country contributing the largest number of citations is more evident in the citation sample excluding BaBar; however, the major features of the citing country distribution are similar over the two data samples, apart from the more prominent position of Japan in the sample excluding BaBar.

The distribution of institutes citing [2] is strongly biased by BaBar citations. It is led by INFN, followed by a long list of
TABLE I
Geographical areas of the citations to [2].

| Geographical Area                  | Percentage (%) |
|------------------------------------|----------------|
| Europe                             | 69             |
| North America                      | 49             |
| Asia                               | 31             |
| Russia + former Soviet Union countries | 27         |
| South America                      | 2.4            |
| Oceania                            | 2.4            |
| Africa                             | 0.9            |

TABLE II
Geographical origin of the citations to [2]: top 10 countries.

| Country   | Citations (%) |
|-----------|---------------|
| USA       | 47            |
| Germany   | 32            |
| Italy     | 30            |
| France    | 29            |
| England   | 28            |
| Russia    | 26            |
| Spain     | 25            |
| Canada    | 22            |
| Netherlands | 21         |
| Scotland  | 19            |

TABLE III
Geographical origin of the citations to [2]: top 10 countries, excluding citations associated with the BaBar experiment.

| Country   | Citations (%) |
|-----------|---------------|
| USA       | 35            |
| Germany   | 18            |
| Italy     | 16            |
| Switzerland | 15         |
| France    | 15            |
| England   | 14            |
| Japan     | 13            |
| Russia    | 11            |
| Spain     | 10            |
| Canada    | 6             |

B. Research areas

The journals providing citations to [2] encompass a widely multi-disciplinary scope; they include particle and nuclear physics, technology, astrophysics and medical physics journals, and fields as diverse as geophysics, plasma science and materials science. The top 10 are shown in Fig. 7; the statistics are based on 1086 citing papers. Regarding NIM, both the total number of citing articles, and the number resulting from the exclusion of conference proceedings papers are shown; in the latter case no further renormalization was performed to account for the modified citation sample size in the calculation of the fraction of papers relative to the other journals. Multi-disciplinary technology journals appear to be the major source of citations, together with HEP publications in Physical Review D and Physical Review Letters.

The references to [4] exhibit a different pattern: while for [2] technology and physics journals are the major sources of citations, medical physics journals, together with TNS and NIM, originate most of the citations to [4]. However, due to the

TABLE IV
Origin of the citations to [2]: top 10 institutes.

| Institute                                   | Citations |
|---------------------------------------------|-----------|
| INFN                                        | 288       |
| Rutherford Appleton Lab.                    | 207       |
| Univ. Milan                                 | 205       |
| Univ. Liverpool                             | 203       |
| Univ. Valencia                              | 203       |
| Harvard Univ.                               | 199       |
| Univ. Padua                                 | 199       |
| Univ. Roma La Sapienza                      | 199       |
| Univ. Calif Los Angeles                     | 198       |
| Ohio State Univ.                            | 196       |

TABLE V
Origin of the citations to [2]: top 10 institutes, excluding references associated with the BaBar experiment.

| Institute                                   | Citations |
|---------------------------------------------|-----------|
| INFN                                        | 105       |
| CERN                                        | 82        |
| Univ. Tokyo                                 | 42        |
| Univ. Valencia                              | 37        |
| Kyoto Univ.                                 | 34        |
| Russian Acad. Sci.                          | 28        |
| JINR                                        | 26        |
| Univ. Oxford                                | 26        |
| Univ. Sheffield                             | 26        |
| Rutherford Appleton Lab.                    | 25        |

TABLE VI
Origin of the citations to [2]: top 10 institutes, excluding references associated with the BaBar experiment and CERN authors.

| Institute                                   | Citations |
|---------------------------------------------|-----------|
| INFN                                        | 70        |
| Univ. Tokyo                                 | 39        |
| Kyoto Univ.                                 | 28        |
| RIKEN                                       | 21        |
| Univ. Valencia                              | 21        |
| Vanderbilt Univ.                            | 21        |
| NASA                                        | 20        |
| Univ. Liverpool                             | 20        |
| Univ. Michigan                              | 19        |
| Harvard Univ.                               | 18        |
limited statistical significance of the citation sample associated with [4], it is hard to derive any firm conclusions from this observation.

An effort was invested to identify the research areas from which the citations to [2] derive, and to estimate their relative contribution quantitatively. In some cases the identification was straightforward: for instance, papers published in journals characterized by well-defined scope (e.g. Medical Physics, Physical Review D etc.) were attributed to the related research domain. Other criteria involved the association with experiments, projects and research groups, whose scope of activity is well known in the community. The papers which could not be attributed to a research area by means of automated criteria were inspected manually by examining the abstract and, in a few cases, the whole article. This analysis involved some degree of subjectivity; nevertheless, we do not think that it introduced any significant bias in the results. The amount of noise and the incompleteness of the data samples deriving from automated searches affect the conclusions of the various analyses; the uncertainties of the results as determined from manual inspection are smaller than 5%.

The distribution of research areas contributing citations to [2] is shown in Fig. 8; it is based on the sample of 1086 papers. High energy physics appears the major source of citations; nevertheless, if BaBar papers are excluded, the contribution from medical physics becomes comparable to the one from the rest of HEP. This result confirms the observation in [1] that, while Geant4 development was originally motivated by high energy physics requirements and many of its developers are affiliated with high energy physics laboratories and institutes, Geant4 use extends far beyond high energy physics; the present analysis provides the first quantitative estimate of Geant4 application to different scientific research areas.

The 418 papers associated with HEP research were further classified according to their pertinent experimental sub-domain. The analysis involved manual inspection of the publication records (abstract and full paper) in the cases where automated criteria could not identify the proper attribution of a paper. The results are shown in Fig. 9.

By far, the largest number of HEP citations are associated with BaBar. It is worthwhile remarking that 59% of the physics papers published by BaBar over 2004–2008 cite Geant4; this observation confirms the strategic role played by Monte Carlo simulation, and Geant4 in particular, in the physics analysis of HEP experiments. The indications coming from BaBar can be extrapolated as similar expectations for the LHC experiments, which have based their simulations on Geant4.

The second largest source of HEP citations is astroparticle physics; somewhat surprisingly, at this stage the citations from this field outnumber those related to LHC, whose experimental program motivated the development of Geant4. However, these results should be revisited after LHC becomes operational and the LHC experiments start publishing physics results.

V. Missing Citations

The Geant4 citation patterns in Nuclear Instruments and Methods A and IEEE Transactions on Nuclear Science reported in [1] showed that Geant4 is not properly cited in many cases. This analysis was extended to the larger data sample now available in these technology journals and to two additional data samples: a set of physics journals (the Physical Reviews, published by the American Physical Society) and the multi-disciplinary collection of journals published by Elsevier.

The analysis concerned papers published in 2004–2008, where Geant4 is mentioned in text; it verified whether they properly cite [2]. The results concerning the fraction of proper citations in NIM, TNS and the relevant subset of Physical...
TABLE VII
FRACTION OF PAPERS PROPERLY CITING [2]

| Journal        | Percentage (%) |
|----------------|----------------|
| NIM A and B    | 51             |
| TNS            | 59             |
| Phys. Rev. C   | 68             |
| Phys. Rev. Lett.| 93             |
| Phys. Rev. D   | 81             |

Reviews are summarized in Table VII. The papers published in physics journals appear more diligent at properly citing Geant4 reference than those in technology journals. However, with respect to the data reported in [1], the fraction of properly citing papers in NIM has significantly increased, while it has remained approximately constant in TNS.

A similar analysis over the whole Elsevier journals collection found that 40% of the publications in these journals correctly cite [2], when Geant4 is mentioned in the text.

The more recent Geant4 reference [4] appears to be seldom cited: only 27% of TNS articles and 10% of NIM ones published in 2007-2008 properly cite it, when Geant4 is mentioned in the text. Hardly any paper cites it in fundamental physics journals.

VI. CONCLUSION

This study documented a detailed, quantitative analysis of citation patterns related to Geant4. It highlighted the major role played by Monte Carlo simulation both in fundamental nuclear and particle physics research, and in related technological research; this role has become more visible when considering the years 2000-2008 as compared with the years 1990-1999.

Geant4’s first reference paper has rapidly become the most cited publication in Nuclear Science and Technology. Nevertheless, the use of GEANT 3 remains widespread in particle and nuclear physics experiments, and is documented in recent publications of physics results.

The Geant4 user community is largely multi-disciplinary, with high energy physics and medical physics contributing the largest numbers of citations. Within HEP, the BaBar experiment and the astroparticle community have published the largest number of papers citing Geant4. However, this paper reflects the citation sample as in October 2009, a few weeks before the beginning of LHC commissioning phase; the results concerning HEP may be subject to change, when LHC starts operating.

Along with the large number of citations collected by Geant4, a large number of publications do not cite references for the code they use. There are a number of reasons for this pattern, including authors considering Geant4 to be a public domain facility, a perception that it is not the result of scientific research, or the fact that many well-known Monte Carlo codes lack an associated reference publication in a peer-reviewed journal.

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