**Collaboration methods in particle physics and biology**

Particle physics investigates the fundamental building blocks of the Universe. It requires large experimental efforts and very expensive equipment, for example particle accelerators. This has led to the progressive development over the last decades of advanced methods for large scientific collaborations. These methods facilitate the open discussion of new ideas, the planning of experimental approaches, the design and management of large facilities, the running of experiments, the communication of results in scientific articles and the evaluation of scientific knowledge. Here we present an introduction to these different steps.

**Snowmass Process and other planning aspects**

The Snowmass process is a community study and planning process for the next two decades organized by particle physics scientists in the US. It is named after the place where it was first held in 1982 and it takes place every 5-10 years. As described on the website (snowmass21.org) “Snowmass is a scientific study. It provides an opportunity for the entire particle physics community to come together to identify and document a scientific vision for the future of particle physics. … Snowmass will define the most important questions for the field of particle physics and identify promising opportunities to address them.”

The most recent meeting has taken place on July 17-26 2022, after a one-year COVID-related postponement, and was preceded by two years of online and small group discussions, which produced more than 1500 letters of interest (2-page documents) and more than 500 white papers (snowmass21.org). Many of these were co-authored by teams of scientists. The first Snowmass in 1982 consisted only of a three-week-long meeting but it has now evolved to include not only the preparatory activities mentioned but also online discussions on slack, surveys and efforts to promote the participation of early career scientists.

The discussions and report preparations were divided into 10 frontiers focusing on different aspects of particle physics and coordinated by conveners. Each frontier was subdivided in 6 to 11 topic groups (for a total of 81) that also meet separately. Great care is taken to promote interactions between groups and frontier, encouraging multiple memberships and joint meetings, so that the integration of subfields is achieved. The initial focus is on making sure that every voice is heard, and prioritization choices and budget constraints are not explicitly considered.

The report from the Snowmass process merges the discussions from all the frontiers and is sent to a separate panel organized by the Department of Energy (DOE) and by the National Science Foundation (NSF). This is called the Particle Physics Project Prioritization Panel (P5) which provides specific recommendations with cost scenarios that eventually are sent to DOE and NSF and to Congress for funding decisions. The DOE is the main funder of particle physics in the US. After the last P5 report, in 2014, the community was consulted again and 2,331 signatures on a letter of support were gathered (Jepsen, 2022).

A similar process in Europe is called the European Strategy for Particle Physics. The latest of these took place in 2018-2020. There is close international coordination and the largest experiments, like those at the LHC at CERN, are supported by multiple countries.

It is worth examining how inevitable divisions among specialists in different subfields and approaches are balanced to reach a common overall plan. Already in the first Snowmass report in 1982 Richard Gustafson (Gustafson,1982) wrote: “The summer study succeeded in exploring new accelerator technology and ideas, consequences of the new conventional physics, and a few new physics ideas. It also brought together a good sampling of the individuals involved in current and near future high-energy physics enterprises. A large number of ideas and opinions were exchanged and partially reconciled. The DOE and NSF agencies both had participants/representatives involved in the study, mixing with the participants. There was a fair balance between the politicians, who came with axes to grind, papers in their pockets, and who worked popularizing their causes, with those who explored new ground and ideas. All the participants left Snowmass with a greater sense of the high-energy physics scientific community, their role in it, and their goals for it. The study was a tremendous success for the field.”

In 2020 a senior scientist that participated in and contributed to organize multiple previous Snowmass editions, Chris Quigg, was asked to provide an introduction called “How to Snowmass” (Quigg, 2020), where he wrote: “A certain amount of advocacy for projects or lines of research is inevitable, even desirable. Engage with initiatives other than your own and bring to them a fresh perspective. Probe for weaknesses, to be sure, but ask how you can make them stronger. My goal would be that every initiative might emerge better understood, improved, and taken more seriously after *Snowmass 2021* than before, and that the seeds of new initiatives might be gathered. Even if some ideas do not emerge as priorities today, they might in the future, so it is to our advantage to develop them as convincingly as we can and to identify what needs to be done to bring them along.”

DOE feedback had a role in promoting cooperation. A paper describing the 2013 Snowmass (Cho, 2020) stated: “Most important, DOE officials warned, the squabbling and backstabbing had to stop. In fact, physicists recall, the 2013 process had an informal motto: “Bickering scientists get nothing.” This motto was in fact also repeated by a DOE associate director in a 2014 interview (Lucibella, 2014) and was also shown in the slide presentation from DOE at the beginning of the 2022 Snowmass (Kung, 2022). It seems that a balance between open and frank discussion and cooperation is obtained by reminding participants that they are not competing for a fixed amount of resources but that to some extent they are making a scientific case that will determine the size of this support.

Feedback from DOE, however, was not the only factor to affect the evolution of community level planning in particle physics. This field has undergone two recent planning crises. The biggest was certainly the cancellation of the Superconducting Super Collider (SSC) in 1993, after almost 2 billion dollars had already been spent. One of the main reasons for the cancellation was the decreased political motivation for prestigious national projects caused by the end of the Cold War (Kevles, 1997). Another setback was the slashing of planned funding for the International Linear Collider (ILC) in 2008, as consequence of the economic situation (Hand et al, 2008). The challenge in obtaining stable political support is commonly explained by the lack of direct short-term benefit for society, even if indirect benefits have been clear, as in the case of the development of the world wide web at CERN (Weinberg, 2012). This challenge has motivated increased collective efforts by particle physicists. Quigg explicitly stated (Quigg, 2020) that the 1996 Snowmass meeting was organized to help the community regroup after the SSC cancellation.

There are signs that these efforts have been progressively more effective. The Particle Physics Project Prioritization Panel (P5) was started in 2003, but the P5 reports in 2003 and 2008 did not mention the Snowmass process and were not closely integrated with it (P5 Report, 2003; P5 Report, 2008). This changed with the 2014 P5, chaired by Steven Ritz (P5 Report, 2014). In that report the Snowmass community study was cited 14 times and in his testimony to Congress in the same year (Ritz, 2014) Steven Ritz stated that: “A yearlong community-wide study, called “Snowmass”, preceded the formation of our new P5. A vast number of scientific opportunities were investigated, discussed, and summarized in Snowmass reports. Based on this comprehensive work by the broad community, we identified five compelling lines of inquiry that show great promise for discovery over the next 10 to 20 years … The work by P5 grew directly from the preceding community-wide study, and there was a continuous effort on many fronts throughout the P5 process to maintain direct community engagement, including workshops, physical and virtual town halls, consultations, presentations, and a public submissions portal.” Congressional appropriations for particle physics increased substantially in the following years and appropriation reports contained language strongly supporting the P5 and praising the accomplishments of this physics community (Turner K, 2019).

Abraham Seiden, the chair of the first P5 pointed out in 2021 that: “Steve Ritz, who was our next director at SCIPP, he chaired the next P5, and that one actually made a plan that was very influential. Completely influential in that the community and funding agencies have followed it since then. So it laid out the HL LHC upgrade as the major future project, the neutrino program as being the most important U.S. project, and a number of other projects including particle astrophysics and so that plan actually has been followed and has been very important in guiding the program in particle physics at both DOE and the NSF.”

A very recent review from particle physics community leaders (Butler et al, 2022) stated: “We hope that … our report will help P5 produce recommendations that the community can unite behind, as it did in 2014. This is a proven effective step in convincing the public and government policy makers that we have conducted a rigorous process and achieved a consensus that is worthy of their support.”

**Large Instruments and Facilities**

Some of the largest particle physics instruments and facilities require investments of billions of dollars. Among these are particle accelerators like the Large Hadron Collider (LHC) at CERN in Geneva, supported by collaborations among multiple countries and by teams of thousands of scientists from many nationalities.

**Large experiments**

Large experiments are conducted by teams of thousand or hundreds of scientists. Among these are those based at CERN (for example ATLAS, CMS) and at Fermilab (for example DUNE, Muon g-2). The coordination is usually influenced by the team member choices, and it is not top down.

A remarkable collaboration is ATLAS, which is one of the largest collaborative efforts ever attempted in science. It has over 5500 members and almost 3000 scientific authors, coming from 42 different countries (ATLAS Collaboration). They state that “ATLAS elects its leadership and has an organisational structure that allows teams to self-manage, and members to be directly involved in decision-making processes. Scientists usually work in small groups, choosing the research areas and data that interest them most. Any output from the collaboration is shared by all members and is subject to rigorous review and fact-checking processes before results are made public. The success of the collaboration is bound by individual commitment to physics and the prospect of exciting new results that can only be achieved with a complete and coherent collaborative effort.” (ATLAS Collaboration).

All the members are authors of the main ATLAS papers but there are mechanisms to document and recognize individual contributions, including authorship of shorter internal publications. Leading contributions are also recognized by asking the person in question to present results at conferences (ATLAS Fact Sheet).

Multiple large experiments are often planned to run in parallel, for independent confirmation and to explore different approaches. Examples are the UA1 and UA2 experiments at CERN in 1980s that led to the discovery of W and Z bosons, the CDF and D0 experiments at Fermilab that led to the discovery of the top quark and the ATLAS and CMS experiments at CERN that led to the discovery of the Higgs boson in 2012.

**Scientific Publications**

Scientific papers reporting results from large collaboration often have hundreds or thousands of authors, listed in alphabetical order. Attribution of specific credit for hiring and promotion decision is obtained from letters provided by project and group coordinators, highlighting the contributions of an individual scientist.

The particle physics community played a pioneering role in the development of websites for the rapid online sharing of preprints, before journal reviews. ArXiv was started in 1991 and is now use extensively by physicists and by other quantitative scientists, continuing an earlier tradition of rapid sharing of paper preprints. This experience influenced the later development in 2013 of BiorXiv, which is rapidly growing in acceptance by the biological community.

**Summary of knowledge in the field**

The Review of Particle Physics is the most cited publication in particle physics. It is updated every two years by a collaboration of hundreds of international authors which are part the Particle Data Group. This publication summarizes and organizes the current knowledge about particles and fundamental interactions and consist of a work of more than 1,200 pages. It is distributed freely online (Workman et al, 2022).

**Biological comparisons**

These collaboration methods will be compared with those used in past large-scale biomedical projects, like the Human Genome Project, which was more hierarchical and planned by a small group of experts. The reasons why a research project in cell-cell communication might benefit from approaches inspired by the particle physics examples will be explored.

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