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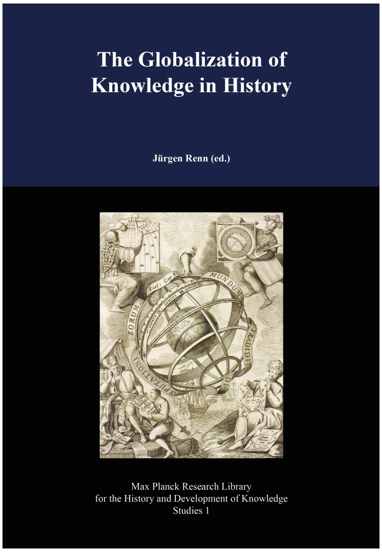
Hans Falk Hoffmann:
The Role of Open and Global Communication in Particle Physics



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Chapter 28
The Role of Open and Global Communication in Particle Physics

Hans Falk Hoffmann

> The Organization shall provide for collaboration among European States in nuclear research of a pure scientific and fundamental character, and in research essentially related thereto. The Organization shall have no concern with work for military requirements and the results of its experimental and theoretical work shall be published or otherwise made generally available.[1]

28.1 Introduction

For over six decades the scientists and engineers of particle physics together with their funding agencies have undertaken the global management of their science, with visibly good results. An open, unrestricted, transparent and fertile environment is provided for all sustainably funded and interested scientists by sharing expenditures globally. All findings of the science, both scientific and technical, are available to anyone who is interested, anywhere in the world. The participating scientists or engineers have and exercise the possibility to speak their minds and to engage in the decision-making-process of this critically communicating, all-hands-involved and democratic science.

For around twenty years, efforts have been in progress to make such newly arising knowledge generally available online. Before the availability of electronic libraries, publications were generally distributed as preprints, advance copies of papers submitted to refereed journals. Today, "open access" or "OA publishing" on the Internet has been adopted almost universally in this science. A "public domain" or a "commons" of sharing and owning knowledge, resources, relationships of trust, collaboration and of efforts is an integral part of this science. These commons are accessible to all other sciences, at least via OA publishing.

This chapter will introduce the science and its governance, explain its open, democratic, self-organizing and collaborative methods, its sharing of insights, its modes of global "agenda setting," its detailed processes of decision-making and

[1] From the "Convention for the Establishment of the European Organisation for Nuclear Research, CERN," ratified in 1954 by its member states, published, for example, in Germany in (BGBL 1954).

quality control, and undertake to show the added value and also the inconveniences of this way of doing science. It will not attempt to demonstrate the difficult, tortuous and sometimes chaotic paths and scientific reflections of individuals or communities that are necessary to move from one particular scientific model to the next.[2] It is not concerned with the particular scientific or technological choices that are made, or why, but it will point out the ever more complex instruments and, in particular, the e-infrastructure required to allow all participants to be fully aware of all forms of knowledge relevant to the progress of the science. The evolution of the CERN LHC project, its accelerator and its experiments, occupying more than half of the global community of particle physicists, will be used to demonstrate the principle point of the paper:

> All knowledge, skills and know-how within this science are common goods, elaborated in a continuous and structured dialogue between equal partners, available without restriction to all participating scientists, supported by a powerful electronic infrastructure to make them available to all participants immediately and everywhere. The community values every scientist's opinion and encourages intense communication and exchanges of opinions. Hierarchies are rather flat.[3]

Particle physics and other cosmic sciences are rather unique examples of fundamental sciences since they are mostly free from external influences such as political, military or commercial requirements. They enjoy considerable public interest in their complex, innovative instruments and their fundamental subjects, which describe important aspects of the evolution of our universe. They also create interesting, unsolicited and sometimes spectacular spin-offs. Obvious examples are the creation at CERN of the World Wide Web in 1989/90 and its positioning in the public domain[4] or the use of particle physics instruments for radiotherapy and medical or technical diagnostics. Most importantly, every year particle physics attracts, educates and releases into industry or academia thousands of young scientists and engineers.

In contrast, and not in "cosmic" sciences, the use and availability of knowledge changes drastically when military superiority or industrial profits from scientific

[2]See, for example, (Renn 2006).

[3]This is the author's view of the workings of a collaboration in particle physics from decades of working within such collaborations. One ingredient is the CERN convention (see footnote 1) and its requirement to make all findings generally available. The formal organization statements of the collaborations demonstrate another aspect as they represent the community's decisions of how they want to collaborate in practice. The ATLAS organization can be taken as typical example from the ATLAS technical proposal (LHC Experiments Committee 1994, chap. 10.5.1, 205). The ATLAS organization chapter describes the roles and responsibilities of every member and every institute of the collaboration as well as of all officers of the collaboration and their limited terms of office and regular election processes. The ultimate authority is the regular "all hands plenary meeting."

[4]Compare, for example, "The World Wide Web Consortium (W3C)": http://www.w3.org. A description of the Web's history can be found in (Gillies and Cailliau 2000).

applications promise exclusive advantages. Free communication, the availability of data, information or results and information on potential applications is then severely channeled, restricted or suppressed. Equally, the advances of scientific efforts which are dominated by restricted availability of knowledge and by research agenda-setting following non-scientific interests make sciences appear to progress more slowly or in a biased fashion toward their general, high-level goals.

Following the example of complete openness that is typical for fundamental research, there is a growing tendency to establish similar openness in other fields, particularly in medicine and the life sciences,[5] claiming that publicly funded research should make its results generally available as a public good. Between the restrictive proprietary use and availability of knowledge generated by industries or for military purposes and the generally available knowledge, there is a wide area of application of knowledge and setting of research goals where the public good should be favored over private interests. Many voices challenge the present balance, which seems to be more on the side of private, even if multinational, or national security interests.

Thus, the use of knowledge and the unbiased setting of research agendas have become a prominent side issue of global governance. Here are some examples: The recent UN/ITU World Summit of the Information Society expressed in its declaration of principles its

> […] common desire and commitment to build a people-centered, inclusive and development-oriented Information Society, where everyone can create, access, utilize and share information and knowledge, enabling individuals, communities and peoples to achieve their full potential […]

The declaration further promotes a dedicated strategy of sharing scientific knowledge, technological skills and best practices in science education and applications as essential for the development of less developed countries.[6]

The European Research Council has begun to speak about the desirability of a fifth European freedom: the free circulation of knowledge and the conditions to make it happen.[7] This is in complement to the four established freedoms of the EU: the free circulation of goods, capital, services and persons.

Indeed, between the strictly proprietary, profit- or military-oriented endeavors and fundamental scientific goals, there is a large spectrum of global priority goals which would be better treated with global interests in mind and with all available knowledge at the disposal of all scientists concerned. Examples of such possible global goals are evident in the UN Millennium Development Goals, or

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[5]For example, the public accessibility of research sponsored by the US National Institutes of Health: http://publicaccess.nih.gov.

[6]See (WSIS 2003), cf. also (Dosanjh and Wilkinson 2004).

[7]See (CORDIS 2007) or (ERA 2007).

more specifically concerning health in the “Global Burden of Disease” reports of WHO,[8] both of which are concerned with the majority of the world population.

Public research and education, health, poverty and hunger, climate and sustainable energy provision, biodiversity and sustainable environment are amongst the promising subjects for global knowledge based approaches. The global communication, sharing and governance practices and the commonly constructed and used infrastructures described here may provide “food for thought” for other sciences and their global self-governance. In particular, the role of intellectual property from publicly supported science should move from individual exploitation toward a more common availability.

28.2 Particle Physics: A Global Science

28.2.1 The Science

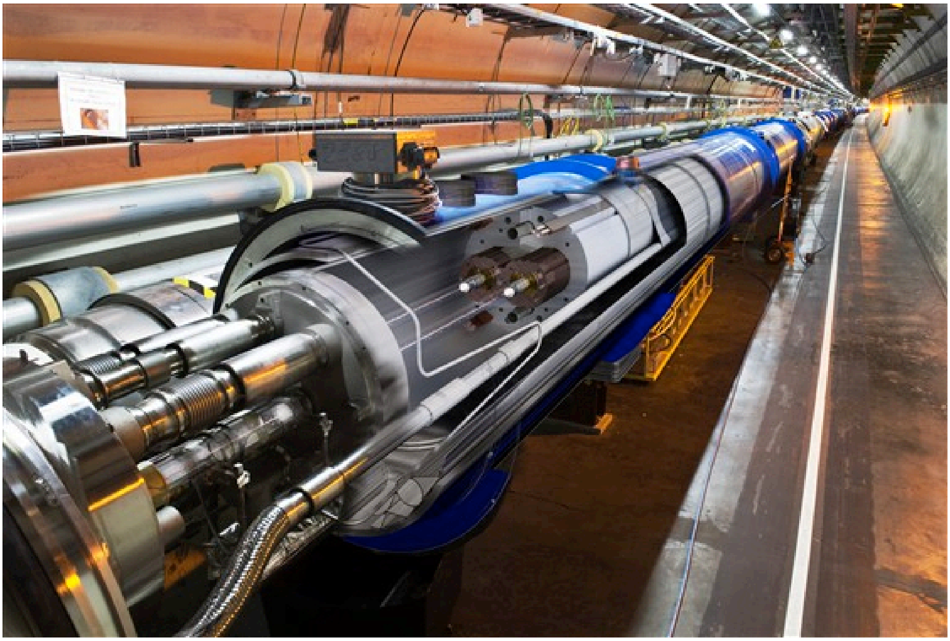

Figure 28.1: Superconducting Magnets of the LHC. (CERN-AC-0911188 01 ©CERN)

[8]Compare, for example, the “UN Millennium Development Goals”: http://www.un.org/millenniumgoals, and the WHO “The Global Burden of Disease”: http://www.who.int/healthinfo/global_burden_disease/en.

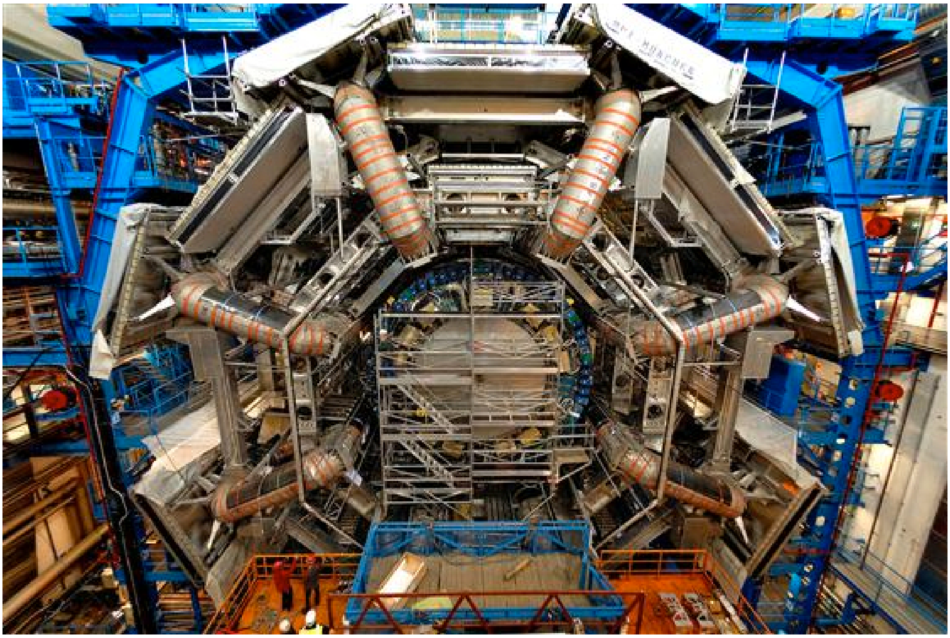

Figure 28.2: ATLAS experiment during assembly. (CERN-EX-0610006 ©CERN)

Thanks to fundamental research in physics, we know that all the matter we can see in the Universe is made up from a handful of elementary particles, and particle physics can tell us with good precision about the way these particles interact among themselves. However, we also know that what we see in the Universe accounts for only a few percent of what we know to be there. About the rest, named dark matter and dark energy, we know almost nothing.

That we occupy such a small fraction of our Universe is fascinating, and extending our knowledge here is in itself a good reason for pursuing this fundamental research. With the Large Hadron Collider project today in construction at CERN (compare Figures 28.1 and 28.2), we hope to undertake some further steps to find some missing details of the known 5% and clues as to what the remaining unknown 95% are, and how they relate to the familiar 5% that we inhabit and know.

The method of particle physics is to explore matter at very small distances or, equivalently, at very high temperatures or energies. To this end, using accelerators elementary stable particles such as protons or electrons are brought to collision at ever-higher energies. The available energy of the moving particles in the center of mass system of the collision partners is available through the "matter – energy – equivalence" to create new particles. International collaborations conceive and construct experiments to observe such collisions.

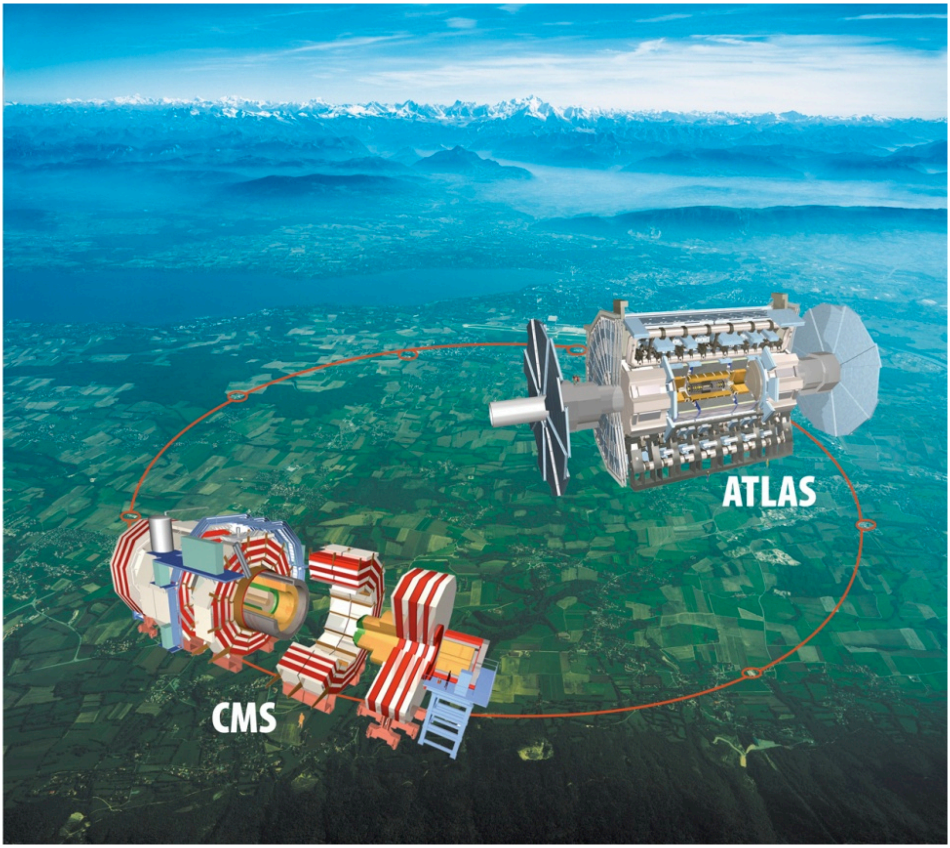

Figure 28.3: The 27km underground tunnel of the LHC accelerator (red circle) and cut-away drawings of CMS and ATLAS at the position of their underground collision areas. (CERN BUL-PHO-2009-064 3 ©CERN)

The LHC project[9] is a European and now global project consisting of a 27 km-circumference, superconducting accelerator for creating high-energy collisions with temperatures as high as the temperature of the universe a small fraction of a second after the big bang. Two "general-purpose" experiments, ATLAS[10] and CMS[11] are conceived to observe the behavior of such collisions as completely as

[9]Technical papers describing the LHC and its experiments can be found in the special edition of the electronic journal *JINST*, the Institute of Physics (IOP) electronic *Journal of Instrumentation*: http://www.iop.org/EJ/journal/-page=extra.lhc/jinst. A more popular description of the LHC accelerator and the corresponding experiments can be found in (Evans 2009).
[10]ATLAS homepage: http://atlas.web.cern.ch/Atlas/index.html.
[11]CMS homepage: http://cms.cern.ch.

possible (see Figure 28.3). Among the main subjects of interest derived from particle physics theories and past findings are Higgs-searches or alternative schemes for the spontaneous symmetry-breaking mechanism, searches for super symmetric particles, dark matter, effects from extra dimensions, new gauge bosons, lepto-quarks, or quark and lepton compositeness indicating extensions to the Standard Model and new physics beyond it.

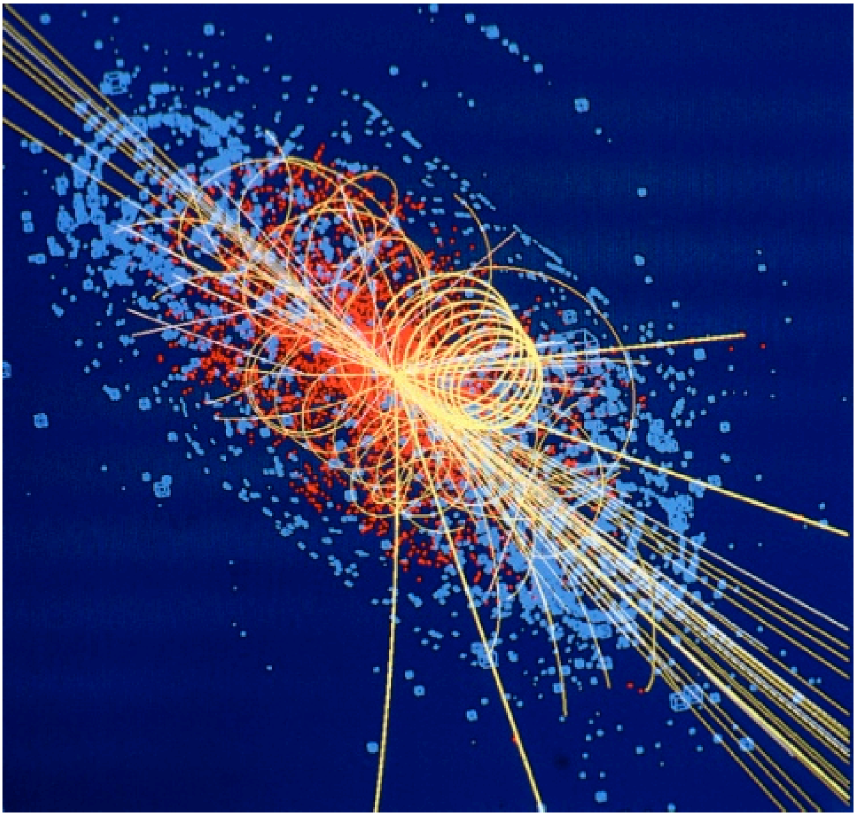

Figure 28.4: CMS simulation of a Higgs-boson decay to four muons. (CERN-EX-9710002 1 ©CERN)

There are two such experiments, made by independent and competing collaborations, which serve as an ultimate quality control to substantiate any findings of new physics. Even then, competition applies for discoveries only and there is exchange in technologies, accelerator-experiment interfaces and other matters. Two more experiments specialize on specific aspects of the collisions, LHCb[12] on the

[12]LHCb homepage: http://lhcb.web.cern.ch/lhcb.

differences of matter and antimatter states of the b-quark and ALICE[13] on heavy ion collisions. There are some smaller experiments.

Figure 28.4 shows an example of a simulated collision modeled for the CMS detector of the Large Hadron Collider LHC at CERN, producing a Higgs boson in a 14 TeV collision of two protons, entering along the diagonal and colliding in the center of the figure. The Higgs boson decays almost instantly into four muons, the rather straight yellow lines at larger angles. Collisions in the LHC occur at random and an event such as is shown in the simulation—event production and branching ratio into detectable decays—happens very rarely, at a level of 1 in ~10^{13} to 10^{14} of all collisions. For comparison, the straight tip in lotto is about 1 in 10^7, one to ten million times more frequent. Understanding such rare events requires studying and understanding all the physical processes that generate events in sufficient detail to be able to select the rare and interesting ones unambiguously.

The useful lifetime of LHC and its experiments is estimated at ten to twenty-five years depending on scientific output and potential upgrades. During such a time span, a phenomenal amount of data will have to be selected, stored and analyzed.[14] The scientific potential of LHC corresponds to the expectations of the majority of the global particle physics community, who have regarded the LHC as a priority scientific activity since the mid-1990s, after the demise of the even more ambitious Superconducting Super Collider, SSC project[15] in Texas, USA.

28.2.2 The Community

Particle physics today is spread over most developed and a number of less developed countries, with 15–20,000 scientists and engineers in universities, academies and particle physics institutes, about 600 different institutes in about 70 nations.

In the interest of doing competitive research, scientists in particle physics agree to invest a considerable portion of their available resources in large laboratories capable of providing the required accelerator infrastructures and of providing the community with almost free access to their facilities. A large part of the community aggregates into collaborations to construct and exploit the ever more complex experimental tools that are necessary for the science. Section 28.3 will attempt to explain how individual academic freedom within competent institutes—a prerequisite for successful, curiosity driven research—is preserved and cultivated in such a highly structured environment.

After World War II, eminent scientists, politicians and the UNESCO proposed to return to open, non-military fundamental nuclear science and suggested the construction of large laboratories that could provide accelerators and beam lines for university scientists. Indeed, the first laboratories were then founded: BNL (1947) on Long Island by the US; CERN (1954) in Geneva by twelve member states;

[13] ALICE homepage: http://aliceinfo.cern.ch.
[14] See section 28.4.
[15] See http://en.wikipedia.org/wiki/Superconducting_Super_Collider, and (Riordan 2000).

and JINR (1956) in Dubna by eleven member states. Today, other such major accelerator laboratories can be found in Europe: DESY[16] and GSI[17] (Germany); in the Americas: FNAL and SLAC (US)[18] and TRIUMF[19] (Canada); in Asia: KEK (Japan) and IHEP (China)[20]; and finally in the Russian Federation: IHEP[21].

The principal infrastructure items are the accelerators, beam lines and collision areas with their ancillary technical equipment for the accelerators and experimental equipment as well as in-house shops and engineering services.

In the past sixty years, the collision energies have grown by about four orders of magnitude based on many innovative changes of accelerator technologies used.[22] Similarly, the sensitivity, speed and selectivity of experimental set-ups have undergone even more drastic changes with the development of many novel particle physics detection devices[23] and their integration into multi-purpose devices.

In the 1950s to 1960s the large laboratories conceived, constructed and operated accelerators and experimental facilities such as bubble chambers whereas university teams mostly analyzed data. Today, CERN constructs the LHC with 15% external resources, people and funds. Indications are that a next world accelerator—if ever built—would be constructed in collaboration[24] with order of 50% external contributions, sharing resources and governance on a planetary level. In contrast, the worldwide community outside of the large laboratories already provides 80% of all resources required for the LHC experiments and CERN 20%, demonstrating the deliberate move of skills into the community at large in the past decades.

The funding of particle physics comes from many national sources, which guarantees some stability. The LHC and its experiments are constructed and operating and will be sustained throughout their useful scientific life. Funding agencies are well-disposed toward particle physics since promises of performance, cost and scientific achievement are usually kept. At present, there are enough resources to pursue minor development works for future accelerators and novel features in experiments.

Approximately two thirds of the global particle physics community are currently engaged in the LHC project at CERN.[25] CERN employs a staff of around 2400, of which more than 1000 are academics, mostly physicists and engineers, ~300 work in experimental and theoretical physics, ~150 in computing and ~600

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[16] Desy: http://www.desy.de.
[17] GSI: http://www.gsi.de/portrait/index.html.
[18] FNAL: http://www.fnal.gov; Brookhaven National Laboratory: http://www.bnl.gov/world; Stanford Linear Accelerator Center:http://www.slac.stanford.edu.
[19] Triumf: http://www.triumf.info.
[20] KEK: http://www.kek.jp/intra-e; IHEP: http://www.ihep.ac.cn/english/index.htm.
[21] JINR: http://www.jinr.ru; IHEP: http://www.ihep.ru.
[22] See, for example, (van der Meer 1985).
[23] See, for example, (Charpak 1993).
[24] See (Heuer 2009). See also: International Linear Collider website: http://www.linearcollider.org.
[25] See CERN: http://public.web.cern.ch/public and (Hermann et al. 1987).

in accelerators and infrastructure. About 10,000 scientific users, physicists and engineers from about seventy countries (~5900 from the European member states, ~2800 from the observer countries[26] and 750 from forty other Nations) consider the LHC project and its scientific or technological goals as their principal research subject. Around 20%–30% of them are present at CERN at any time for periods ranging from one year to one day. More than 30% of these scientists are Master- or Ph.D. or postdoctoral students and consequently the whole population changes at a rate of about 20% per year.

Most of these scientists and engineers work in the four large collaborations, ALICE, ATLAS, CMS and LHCb. Their participating institutes define amongst themselves their rules of collaboration, the sharing of resources and governance. Most importantly, they set their own scientific goals and elaborate the corresponding experimental set-ups in competition with other groups.

Apart from these laboratories and collaborations, there are also collaborations that deliver important services to the community:

1. The Particle Data Group[27] is a collaboration of more than 150 scientists, which presently delivers an impressive data curation service for the community's awareness with a comprehensive and state-of-the-art summary of particle physics. For over fifty years, the PDG has been offering peer-review and summaries of all theoretical and experimental findings in particle physics.
2. Event generators—Monte Carlo programs simulating high-energy (LHC) collisions—based on current particle physics phenomenology and recent experimental results are at the interface between theory and experiment and allow the simulation of all that is presently known about a possible creation of new particle physics phenomena or particles, for example, the above-mentioned Higgs particle.[28]
3. The passage of particles through matter, for example, resulting from an event generator, can be described in great detail today in elaborate Monte Carlo simulation codes[29] after many decades of effort starting from electromagnetic showers in matter to include strongly interacting particles and numerous other fine details. Such programs allow the simulation of collisions with hundreds of particles within experimental set-ups consisting of millions of different components represented in their actual shape and material composition.
4. ROOT[30], an open source, "object oriented" software package for storing, mining and analyzing large amounts of data is developed in 'Bazaar-Style'

[26] Currently India, Israel, Japan, Russia, Turkey, and USA.

[27] See http://pdg.lbl.gov and their latest publication (Amsler et al. 2008).

[28] See, for example, (Corcella et al. 2002, 2005). There are many other event generators such as Phytia, Sherpa, and others.

[29] See, for example, GEANT4: http://geant4.cern.ch and FLUKA: http://www.fluka.org.

[30] This is a data storage, mining and analysis software package for physicists, authored by Rene Brun, Fons Rademakers and many others: http://root.cern.ch/drupal; for an introduction, see: http://root.cern.ch/download/doc/1Introduction.pdf.

(Raymond 2001) by a community of interested scientists. ROOT or ideas and parts of it are used in LHC experiments and other scientific efforts.

Many other "service" collaborations exist for developing and pursuing research and design (R&D) in accelerator and experimental technologies.

Theoretical physicists reside mostly in universities and academies, but all large laboratories have theoretical physics groups and offer a small number of prestigious positions. With their meeting facilities and the latest experimental findings, accelerator laboratories attract numerous topical meetings, offer fellowships and temporary visiting scientist positions to theoreticians in order to encourage their close interaction with the experimentalists. The theoreticians express in their theories the findings of the experiments in the context of what is known or what might be a new phenomenon. They give scientific input to the desirability of new accelerators and experiments and advise on the interpretation of results. They work on the next and more encompassing theories of particle physics and cosmology. Online publications, e-prints, using for example, *arXiv*,[31] and all other means of communication have made theoretical particle physicists around the world a closely interacting, but mostly unstructured and distributed community.

The most important feature of the whole community is that all knowledge, know-how and particular skills are shared freely and instantaneously, from engineering advances to the latest theoretical hypotheses. Institutes are basically free to choose with whom they collaborate as long as they meet the requirements of the collaboration they want to join.

28.2.3 Governance in Particle Physics: Interplay of 'Informal and Bottom-up' with 'Formal and Top-down'

Member state funding agencies govern the multinational accelerator-laboratories such as CERN (and JINR) by means of a council formed from scientists and government officers from all member states. The council is supported by a scientific policy committee of eminent scientists from the global community and a finance committee composed of financial officers from all member states. Countries contributing significantly to the LHC accelerator obtain observer status[32] and participate fully in all dealings concerning the LHC project.

For national accelerator laboratories, national structures replace 'council' functions. There is a large variety of funding and supervision schemes for universities, academies or other institutes working in particle physics.

Accelerator laboratories conceive and construct their accelerators as part of their own objectives and goals and within their own organizational and supervisory structures. New projects advance only after ample discussions with and positive feedback from the international user community. All new accelerator projects

[31] Open access e-prints: http://arxiv.org.

[32] See footnote 26.

are accompanied by peer review 'machine' committees with members from other accelerator laboratories or universities undertaking accelerator research.

Accelerator laboratories have formalized their relations with a number of committees, created ad hoc to achieve coordination at regional and world level with other such laboratories and the community:

1. The European Committee for Future Accelerators ECFA[33] was set up at the beginning of 1963 on the initiative of Professor Weisskopf, then Director-General of CERN, to provide community feedback to CERN, DESY and other laboratories in Europe and to coordinate their activities involving governments, institutes and scientists. Committee members are proposed by the community and nominated by the member state governments.
2. For over twenty years, a similar committee ACFA[34] has existed for Asian countries.
3. The International Committee for Future Accelerators ICFA[35] plays a role of early exchange and coordination of the particle physics laboratories and the community worldwide. It was founded as a regular meeting of the heads of the major laboratories in the late 1960s to early 1970s to avoid duplication of efforts in particle physics. There are regular annual meetings and global ICFA workshops summarizing the state-of-the-art of particle physics on a regular basis.

The ICFA, however, could not resolve the conflict over the competing projects SSC[36] and LHC. The CERN LHC project survived the competition as the less costly proposal backed by many nations; it eventually integrated the SSC user community.

Experimental collaborations aggregate outside of such governance. However, they face severe and high-level scientific and technical peer reviews throughout their existence. Such peer reviews report to the host laboratory's management and supervisory councils and committees. Any institute may join provided it takes an agreed share of resources for construction, operation and maintenance, and exploitation of the experiments.

Throughout their lifetime, CERN experiments are supervised by "Resources Review Boards" who authorize the use of resources of experiments with participation beyond countries represented in the CERN Council. They also follow the progress of the performance goals. Their proceedings are reported to the Council by CERN management.

Today the ATLAS and CMS collaborations alone each have around 2500–3000 scientific or engineering collaborators who conceive, construct, operate, maintain and exploit their devices. The lifespan of such collaborations is about four decades:

[33]ECFA: European Committee for Future Accelerators, compare http://ecfa.web.cern.ch/ecfa/en/Welcome.html.

[34]ACFA: Asian Committee for Future Accelerators, compare http://www.kek.jp/acfa.

[35]ICFA: International Committee for Future Accelerators, compare http://www.fnal.gov/directorate/icfa.

[36]See footnote 15.

half for construction and half for exploitation, corresponding to several generations of scientists. The yearly budget of each of them for construction, exploitation, and human resources corresponds to the budget of a sizeable international laboratory. However, they are not legal entities in their own right and are represented by CERN. At the end of their exploitation, they cease to exist.

Each participating institute and its funding agency signs a memorandum of understanding (MoU) for the construction and exploitation of the corresponding experiment. The MoU defines the purpose of the collaboration, the participants, the deliverables of each institute, the overall schedule, the internal organization and responsibilities, the deliverables, the facilities and areas of the host organization made available for the experiment, the quality control and the supervising bodies of all funding agencies and the host laboratory. The MoU is not legally binding, but institutes and funding agencies recognize that "the success of the collaboration depends on all its members adhering to its provisions."[37] "Deliverables" are services or equipment attributed with a value in a convertible currency by the collaboration, with precise specifications and predetermined delivery schedules; they are executed under the entire responsibility and with the resources of the corresponding institute. Taking entire responsibility for parts of the experiment producing a deliverable reduces transfer of funds, ensures the use of local competences and mastering of the corresponding technologies by the institute concerned. The collaboration executes a rigorous quality control on all activities and parts, making use of external experts in the particular fields of technologies or sciences involved.

Experiments[38] organize themselves in a "bottom-up" manner guided by principles such as democracy, separation of policy-making and executive tasks, minimal formal organization and limited terms of office. The Collaboration Board, the representation of all participating institutes (about 170), is the policy-making and decision-making body of the collaboration. Every participating institute, CERN for example, has one vote. The Collaboration Board elects the spokesperson of the collaboration after nomination of candidates and in due consultation with the collaboration and with the host laboratory. The spokesperson is responsible to the Collaboration Board for the execution of the experiment. The term of office is three years and re-election is possible with a 2/3 majority. The spokesperson chairs the executive board, which comprises system and main activity project leaders as well as a technical and a resource coordinator. The technical coordinator ensures an overview of all technical matters and their coherence. The resource coordinator oversees all resources and their optimal use for the collaboration. The Collaboration Board approves the Executive Board, its remit and composition. Members are elected for two years, renewable with a 2/3 majority.

[37]From: ATLAS Collaboration, "Memorandum of Understanding for Collaboration in the Construction of the ATLAS Detector"; CERN RRB-D 98-44rev. CERN Archives, restricted access. All construction MoUs of the other LHC experiments were of a similar format; they were followed by "Maintenance and Operation-MoUs."

[38]ATLAS is taken as an example, cf. footnote 34.

28.3 Open Communication: Global Collaboration to Address Complex Science Issues

Conceiving, constructing, operating, maintaining and scientifically exploiting an experiment such as ATLAS or CMS is a complex science issue. We shall use ATLAS to describe the collaborative work that produces and exploits such an experiment. CMS and other collider experiments operate in a very similar fashion. We start with a brief description of the apparatus as presented in Figure 28.5.

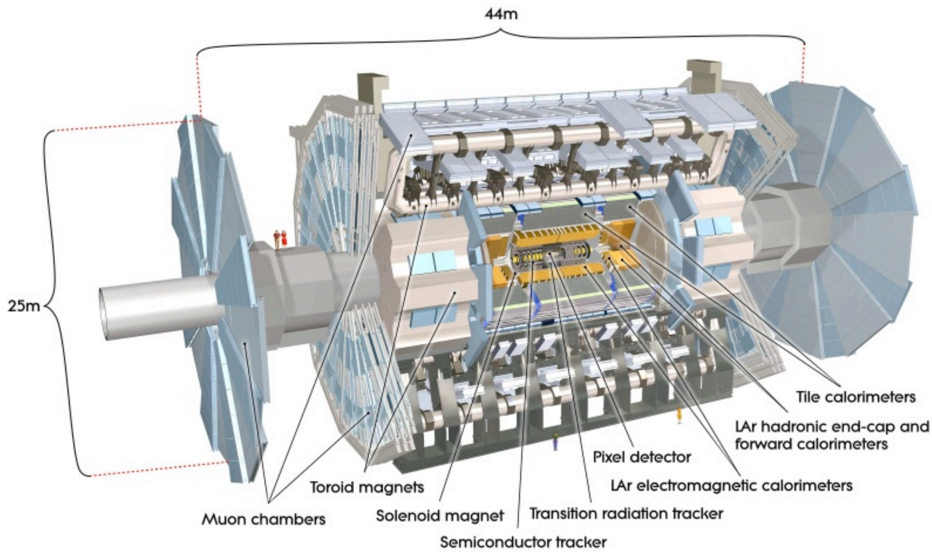

Figure 28.5: Cutaway view of the ATLAS detector. The detector is 25m in height and 44m in length (note the two persons as an indication of size). The overall weight of the detector is approximately 7000 tonnes. (CERN-GE-0803012 05 ©CERN)

The circulating beams of the LHC pass through the center of ATLAS in a vacuum chamber along its axis. Collisions occur inside the "pixel detector." There are one billion collisions per second (10^9/sec) at design rate, each producing around 100 particles. The detector consists of successive shells of detection systems that measure first the position, direction and momentum of all ionizing particles emerging from the collision, then the energy and direction of electrons and photons, then of the hadrons and finally of the muons. The direction and energy of (non-interacting) neutrinos are inferred from missing transverse momentum in the whole event. Momentum measurements require large superconducting magnets creating strong magnetic fields in the tracking detectors. Every detector shell, cable, electronic readout, support structure or magnet element influences the overall precision of the whole device. Therefore, every piece of material inside the experiment needs to be optimized with respect to specific and overall performance. There are millions of pieces.

There are about 100 million electronic detection elements capable of making sense of more than 100 billion particles/sec passing through the experiment during operation. The experiment is capable of selecting online 100–200 events/sec out of the one billion events/sec occurring according to predetermined criteria, mostly large amounts of energy deposited in the detector at large angles away from the incoming beams. This corresponds to a data rate of several hundred megabytes/sec, which are stored for later detailed analysis. Altogether, each experiment creates about 10 million gigabytes or 10 petabytes of already highly selected ‘raw’ data per year from which the new physics is then extracted.

To give a technology timeline, the mid-1980s—the time of the first ideas about what would later become ATLAS—saw the first Apple Macintosh and the first Windows PCs with the Intel 32 bit 386 CPU rated at 16 MHz and a hard-disc drive of 20 MB. The digital content of the entire world was some 20–100 Petabytes.[39] In the mid-late 1980s, workshops on the upcoming accelerator and experiment projects were held. The discussions on detectors, accelerator designs and conditions for experimentation, data acquisition, event generation and simulation within particular detectors and data analysis attracted the attention of many hundreds of scientists.

In August 1987, CERN Council received the report of the long-range planning committee to the CERN Council (CERN 1987) considering the options to open the center of mass range for colliding partons of order one TeV, an order of magnitude more than was possible at the time. It consisted of descriptions of a large hadron collider, LHC, in the CERN LEP tunnel, a large electron positron linear collider, CLIC, a description of potentially interesting physics subjects in the one TeV (constituent collisions) domain and first considerations of the challenges for various parts of experimental apparatus from the mentioned workshops. The design of the LHC accelerator shown presented difficulties due to the size, cost, high magnetic fields and very high beam currents, but proponents considered these to be manageable within the accelerator and technical departments of CERN, given the resources for well-organized R&D work.

In contrast, the main experimental challenge was to make a general-purpose detector able to handle the unprecedented data rates and to distinguish wanted signals of new physics in the presence of a large variety of more standard processes. At that time, existing detectors were capable of addressing rates that were at best two to three orders of magnitude smaller, their granularity or the number of channels again two orders of magnitude lower and with orders of magnitude with lower response and recovery times. Furthermore, the amount of ambient radiation

[39]See the next section 28.4.

when operating the accelerator asked for radiation-hard electronics that did not exist at affordable cost.

Today, the LHC accelerator and the ATLAS and CMS general-purpose experiments exist and operate according the specifications of the early 1990s based on the R&D work undertaken since 1985 and exponential technology advances in electronics, data storage and networking. The very different configuration of ATLAS and CMS at similar overall performance demonstrates that there are several possible solutions to meet the requirements of identifying new physics.

What we see in Figure 28.5 is a large and complex device consisting of millions of parts fitting tightly together. Today, we can see the publication of first results (ATLAS Collaboration 2010; The CMS Collaboration 2010). These are the finished products of two decades of work by 2000–3000 scientists and engineers. This is like watching a main stem river flowing out to sea but being unaware of the countless tributaries flowing in from the many directions and places that have created it. We may assume that the large river diverges again into a number of distributaries, where groups of scientists follow up diverse science subjects or upgrades of the experiment.

How do scientists proceed from first ideas to operating devices that fulfill the original specifications using available resources within a given time? In workshops that took place in the mid to late 1980s, a number of persons with excellent track records from previous experiments invited open and transparent groups of people to co-develop first ideas for novel general-purpose experimental systems. To meet the LHC physics discovery requirements, in numerous iterations they established combinations of potential subsystems from simulations of hypothetical new particles and their detectable decays, embedded into large numbers of more conventional events. Such activities established the required granularity and detection precision of all parts of the detector, setting high-level specifications and optimizing possible overall configurations for the future experiment by successive iterations.

Further iterations concerned, among many other issues, subsystems, looping through choices of detectors, achievable granularity, ease of absolute calibration, available fast, low power and radiation hard electronics, data readout and cables, power requirements, mechanical containers, positioning and obstructions to other parts of the experiment. In a variety and succession of meetings, the scientists involved reported the results which involved all levels of the experiment, from overall considerations down to technical details. Many ideas were discarded, although elements of these were sometimes retained and integrated into further efforts.

A transparent, horizontal, parallel, interactive and iterative multi-technological process looping and iterating through many parallel project designs and system developments was the obvious organizational choice for the participants. Given the unprecedented amount of new and breaking requirements, many competent persons had to work together and compete for the best solutions. Leadership style at all levels was more about stewardship—encouraging participation and crystallizing good ideas in agreement with overall objectives rather than dictating and directing project evolution (Marchand and Margery 2009). The activity leaders were persons of recognized and acknowledged competencies. In the beginning, there was no question of applying traditional project management procedures with their distinct steps of requirements, design, implementation, verification, operation and maintenance, each step following the next like water cascading down steps: many technologies did not even exist in applicable form at the time when, for example, detector choices had to be made. Such project management procedures were exercised only for production when all ideas had been clarified.

The hierarchical structures normally attached to project management seemed to be inadequate. The participants were highly motivated by the scientific objectives, by the competition for best ideas, concepts or technologies, taking note of their increased powers of development enabled by collaborating with many colleagues with a large variety of skills. The prerequisites for such useful collaborations were openness, competence, tolerance, patience, trust, common interests and objectives as well as respect and hard work. Communicating under such conditions produces novel and excellent solutions.[40]

After several years of brainstorming and intense R&D efforts, four proto-collaborations formulated four initial letters of intent to construct a general-purpose experiment and submitted them to the CERN LHC experiments committee, LHCC, the peer review committe set up to advise CERN management on the quality of the proposed experiments. The LHCC together with CERN management found the four letters of intent to be still inadequate, but a good starting point. They asked proponents to further unite efforts and concepts as only two of the experiments were able to obtain the required resources within the community and from CERN. Two collaborations, ATLAS and CMS, emerged from the previous four, losing some collaborators and acquiring new ones. The CERN management invited the proponents to present technical proposals by the end of 1994. In 1996, they approved ATLAS and CMS for construction on the condition that technical design reports would be elaborated for all relevant components.

Even at that point, the experiments never exited the cycle of continuous communication as new facets of the overall enterprise became important. This is the reason why ATLAS (CMS) had around 40,000 (23,000) well-prepared meetings in the period 2006–2010, with almost 190,000 (120,000) documented contributions.[41] These are the years of ending construction, of commissioning, of preparing for and

[40] On individuals elaborating new ideas in a friendly and consenting environment, see the work of the German poet Heinrich von Kleist (1777–1811): "Wenn Du etwas wissen willst, und es durch Meditation nicht finden kannst, so rate ich Dir, lieber, sinnreicher Freund, mit dem nächsten Bekannten, der Dir aufstößt, darüber zu sprechen [...] Der Franzose sagt l'appetit vient en mangeant, und dieser Erfahrungssatz bleibt wahr, wenn man ihn parodiert und sagt, l'idée vient en parlant" (von Kleist 2008).

[41] The management tool INDICO is described in (Gonzélez et al. 2010). The values quoted above can only be read from an ATLAS or CERN account.

of taking first data and publishing first results. There is no other method for gathering all relevant opinions and studies than by continually presenting all of the details until everything is clear and completely accepted by everyone involved. It is also an excellent way of avoiding errors, pitfalls and unexpected surprises.

The subjects of such meetings and their numbers (in brackets) in the ATLAS collaboration ranged from ATLAS weeks (42), Collaboration Board (25), Executive Board (112), Computing (4600), Inner Detector (3000), Liquid Argon Calorimeter (2400), Tile Calorimeter (1400), Muon Spectrometer (2200), Operation (1300), Physics (5600), National and Institute Meetings (11,800), Trigger and Data Acquisition (3600), Upgrades for high luminosity (1100) and many others, for example, the Combined Statistics Forum of ATLAS and CMS (13). All meetings had numerous local participants and numerous others joining in with contributions and comments by video or Internet from their home institutions. The open, all-encompassing communication culture of particle physics is one of its greatest achievements and *conditio sine qua non* for the progress of this science.

28.4 Information and Communication Technologies (ICT) Infrastructure in Particle Physics

In his address to launch the UK e-Science programme in 2001, John Taylor, former Director General of the UK Research Councils, declared:

> E-Science is about global collaboration in key areas of science, and the next generation of infrastructure that will enable it. […] E-Science will change the dynamics of the way science is undertaken.[42]

An all-encompassing communication, worldwide collaboration, common production and use of data and its complete analysis requires a powerful, supporting ICT-infrastructure. Driven by the needs of their science, particle physicists have employed state-of-the-art technologies in many fields and are among the most demanding and expert users—and even providers—of information and communication technologies.

It was the "web-like structure of CERN"[43] which helped Tim Berners Lee to develop the World Wide Web at CERN around 1990. This information accession and retrieval service on the Internet brought about a revolution in the accessibility of information and knowledge.[44] The Web has greatly advanced the way science is undertaken.

In 2001 after an in-depth, two-year-long review of all the computing requirements of the experiments[45] CERN launched a worldwide computing project called

[42] E-science in the UK as described by its first programme director Tony Hey in *Science* magazine (Hey and Trefethen 2005).

[43] From (Berners Lee and Fischetti 1999, 9). For more background information, see also (Gillies and Cailliau 2000).

[44] His first website was *info.cern.ch*.

[45] See (Bethke et al. 2001).

LHC Computing Grid (LCG).[46] The objective of the project was to provide equal opportunities for data analysis to all scientists participating in the LHC experiments, regardless of the location of their home institutes.

In contrast to the original Web and Web services, which enabled easy access to continuous information, Grids[47] and Grid services in addition enable data and information to be processed within the grid and the results made directly available to the collaborators. Accessing and protecting original and derived data requires strict procedures and access-authorizations by their owners, the collaborators.

Many CERN member states supported the LCG on an ad hoc basis. The LCG's efforts and interest in other sciences have now given rise to a study for a future European Grid Infrastructure (EGI)[48] which is based on national grid initiatives in the EU and feeds into the European e-Infrastructure[49] considerations, US Cyber-infrastructure[50] and similar projects in many other countries.

Today, the Worldwide LHC Computing Grid (WLCG) is a global collaboration of more than 170 computing centers in thirty-four countries with more than 100,000 processors and a ~10-petabyte storage capacity of tape and disc, initially supported by the four LHC experiments and several national and international grid projects.[51] The mission of the WLCG project is to build and maintain a data-storage and data-analysis service infrastructure for the entire high-energy physics community using the Large Hadron Collider at CERN. The WLCG project anticipates operating between 500,000 to 1,000,000 tasks per day and expects 15 petabytes of data from LHC experiments to be stored and processed per year. The first results of the LHC experiments have been published using WLCG resources to the complete satisfaction of the users.

In this context, it may be interesting to compare the LHC experiments' design data rates to all digital data produced and stored yearly on the planet. LHC experiments plan to store 15 petabytes/ year (15 x 10^{15} bytes/ year). We can compare this amount to all data created, replicated and stored worldwide in 2010, around 1000 exabytes[52]—a tenfold increase every five years since many years. Calculating backwards twenty years or four orders of magnitude down to the time of conceiving LHC experiments in 1990, the design data storage of LHC was then at the level of 10% of the total. Interestingly, the present edition of the *Review*

[46] LCG: http://lcg.web.cern.ch/LCG.

[47] See (Foster et al. 2001); see also http://www.globus.org.

[48] European Grid Infrastructure study: http://knowledge.eu-egi.eu/knowledge/index.php/Main_Page. In the wake of LCG and to obtain resources from the European Commission several successive EU grid projects were undertaken under CERN leadership, such as Enabling Grids for E-science in Europe (EGEE): http://www.eu-egee.org. The corresponding US effort is the Open Science Grid (OSG): http://www.opensciencegrid.org.

[49] See http://cordis.europa.eu/fp7/ict/e-infrastructure/home_en.html and http://knowledge.eu-egi.eu/knowledge/index.php/Main_Page.

[50] Report of the National Science Foundation Blue-Ribbon Advisory Panel on Cyberinfrastructure: http://www.nsf.gov/od/oci/reports/toc.jsp.

[51] Figures taken from the LCG web: http://lcg.web.cern.ch/lcg.

[52] From Wikipedia 'Zettabyte': http://en.wikipedia.org/wiki/Zettabyte.

of Particle Properties (Particle Data Group Particle Data Group) for over fifty years the top-level summary of what is known in particle physics, is a 40MB file and the LHC petabytes will be condensed into future editions of that review. However, there is much more to science than high-level summaries.

What else should the scientists preserve and make generally available besides the abstract summary conclusions of the *Review of Particle Properties*, the studies performed, and the technologies developed and combined into powerful devices? All of these have enabled scientists to produce and observe interesting collisions, to observe and record relevant data, analysing it to advance their science.

To address this question, we can summarize what is being recorded. Experiments and accelerators document their detailed technical information in an engineering and equipment data management system, in internal notes and information services, tutorials, technical proposals, design reports and presentations and minutes of meetings. Official releases are made in instrumentation, technological and physics conferences and proceedings as well as in publications in appropriate journals and scientific reviews. There are thousands of theses written on technological and scientific investigations. Accelerator laboratories organize topical schools on important subjects and record them. They also offer academic training lectures and student courses.

To turn only to CERN, its Scientific Information Service (SIS) runs, among other operations, since 1990 an online library, the CERN Document Server (CDS)[53] currently holding a million bibliographic records of which almost half are full-text documents concerning particle physics and related areas. CERN's publication policy stipulates that every effort will be made to publish papers under open access (OA) conditions, as defined by the SCOAP3 initiative.[54] As of the date of this document, 2007, the Creative Commons Attribution ("cc by") license[55] meets these conditions. All papers will mention "Copyright CERN, for the benefit of the Collaboration." CERN will strive to exercise its copyright in such a way as to permit the widest possible dissemination and use of its publications. Every reasonable effort will be made to avoid transfer of copyright to a third party. In terms of the OA discussions, CERN mandates "Green OA" and strives to achieve "Gold OA." Green OA is achieved well beyond the 90% level.

The CERN Scientific Information Policy Board (SIPB) is mandated to look into the preservation of scientific objects and records, meaning physical objects or their representations and also "original data." A first report on a particle physics survey on data preservation, re-use and (open) access has been published.[56] The report states the growing interest in preserving relevant samples of event data. The

[53] An overview of the contents of CDS is given at: http://cdsweb.cern.ch.

[54] "Sponsoring Consortium for Open Access Publishing in Particle Physics" (SCOAP3): http://scoap3.org/about.html and "CERN Publication Policy Open Access and Copyright for the LHC publications" http://library.web.cern.ch/library/OpenAccess/PublicationPolicy.html.

[55] For the attribution license of creative commons, see: http://creativecommons.org/licenses/by/2.0.

[56] For the first results from the PARSE.Insight project, see (Holzner et al. 2009).

greatest challenge is to give a meaningful presentation of the best data produced by the Collaboration. It is also difficult to find the resources to undertake such work. To give an example, years ago many tons of exposed bubble chamber film was given to a chemical firm to extract the silver from the emulsion for resale. Because the measuring tables for precision track measurements no longer existed and calibration data had been lost, it was decided that there was no apparent interest in the community to keep and preserve the film.

Most of the information and data mentioned above is available in digital form. What is missing is a coherent and, most importantly, persistent online-structure for all of this information, as well as powerful search engines and the resources to bring it together. This encompasses high level reviews to experimental-device details and original data sets with a view to make all of this knowledge generally available and to archive and curate the information for long-term use.

28.5 Conclusions

Scientific and technical knowledge is a special commodity, and consuming or sharing this knowledge neither reduces nor impairs it. Most importantly, generally and openly sharing knowledge in its proper context increases the knowledge base of all, fertilizes the creation of new knowledge in new applications, and thus with use the value and applicability of knowledge is increased.

For over sixty years, particle physics has been producing interesting and relevant scientific results within a global community that aggregates in powerful international collaborations that are able to address the most difficult challenges together. Due to its fundamental scientific goals, which are rooted in the tradition of eminent physical scientists of past centuries, and its spectacular facilities and global collaborations, particle physics draws excellent young people to science. They learn skills that are highly appreciated in numerous industries, in other sciences and as well in education.

With its exceptional skills in information and communication technologies and its almost complete openness in disseminating its findings, the particle physics community should engage in even more powerful, structured and curated knowledge dissemination schemes for all its current science and technology, publications, historical records, relevant ‘original’-data and other insights. The *Particle Data Group* collaboration could serve as an organizational example since it has been compiling state-of-the-art particle properties in a permanent review for over fifty years.

We have described the collaborative knowledge acquisition process of particle physics, the complete analysis of all data and the reduction properties of physical objects within theoretical frames. We have further described collaborations with clear common goals, critical mass, open sharing and communication and elaborate quality assurance as the most successful and efficient entities for obtaining significant progress in a fundamental science. In particle physics, the authors are acknowledged for their intellectual property, but content is shared freely in the interest of progressing rapidly toward challenging goals within given resources and time spans. It would be advantageous to apply the process to other sciences and interdisciplinary ventures, in particular, using the evolving and enabling "e-infrastructures."

Making the technological achievements of particle physics useful for applications in other sciences and in industry forms part of CERN's Convention to make its work generally available. Interdisciplinary use of such knowledge, skills, know-how or best practices, however, is quite difficult, mostly since resources are normally science specific. The most promising manner of applying the technologies of particle physics is the adoption of interdisciplinary collaborations that are sufficiently long-term for people to learn how to collaborate efficiently with each other.

Finally, a world "knowledge society" that applies the open sharing and availability of knowledge in a respectful and collaborative way would more rapidly advance many burning issues such as sustainable energies, climate, environment, health, development and even sciences.[57]

A European Commissioner responsible for Development once said:

> It is not the impossible which gives cause for despair but the failure to achieve the possible.

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[57] The views presented here are those of the author and do not necessarily represent CERN's or other particle physics institutes' views.

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