The Geant4 Object Oriented Simulation Toolkit

Maria Grazia Pia[1†]
for the
Geant4 Collaboration

[1]CERN, IT Division, CH-1211 Geneva 23, Switzerland,
E-mail: Maria.Grazia.Pia@cern.ch

Abstract

Geant4 is a toolkit for the simulation of the passage of particles through matter, developed with advanced software engineering techniques. Its application areas include high energy and nuclear physics experiments, space physics, medical physics and radiation background studies.

1. Introduction

Geant4 [1] provides a complete set of tools for all the domains of detector simulation: Geometry, Tracking, Detector Response, Run, Event and Track management, Visualisation and User Interface. An abundant set of Physics Processes [2] handle the diverse interactions of particles with matter across a wide energy range, as required by Geant4 multi-disciplinary nature; for many physics processes a choice of different models is available. In addition a large set of utilities, including a powerful set of random number generators, physics units and constants, Particle Data Group compliant Particle management, as well as interfaces to event generators and to ODBMS, complete the toolkit.

The Geant4 software was developed by RD44 [3], a world-wide collaboration of about 100 scientists from Europe, Russia, Japan, Canada and the United States. Since 1999 the production service, user support and development of Geant4 have been managed by the international Geant4 Collaboration. Many specialised working groups are responsible for the various domains of the toolkit.

The Geant4 source code is freely available [4], accompanied by an extensive set of documentation [5].

2. The role of software engineering in Geant4

Software engineering plays a fundamental role in Geant4. Geant4 exploits advanced software engineering techniques and Object Oriented technology to achieve the transparency of the physics implementation and hence provide the possibility of validating the physics results. The Geant4 software process is based on the Booch [6] Object-Oriented methodology, following an approach of spiral iterations and cycles of design and implementations. User Requirements [7] have been collected in the initial phase of the project and are periodically updated. Problem domain decomposition and Object Oriented Analysis and Design have led to a clear hierarchical structure of sub-domains, linked by a unidirectional flow of dependencies [8]. The Geant4 Object Oriented design allows the user to understand, customise or extend the toolkit in all the domains. At the same time, the modular architecture of Geant4 allows the user to load and use only the components needed.

The first Geant4 production version was released in December 1998, on time as originally scheduled [9].

3. The Geant4 kernel

The Geant4 kernel handles the management of runs, events and tracks.

The Run, Event and Track management allows the simulation of the event kinematics, together with primary and secondary tracks. Tracks created in an event can be hndled according to a user-defined priority; this feature provides the functionality to perform studies of anything from pile-up to trigger and loopers.

The Tracking handles the propagation of a track, determined by the physics interactions.

† Permanent address: INFN, Sezione di Genova, I-16146 Genova, Italy

The tracking system manages various kinds of interactions - occurring at a given time, at a given location, or distributed in space-time, or any combination of them - leading to a generalisation of the traditional classification into discrete and continuous physics processes. In order to fully exploit the validity ranges of the physics models, Geant4 does not apply any tracking cuts, but relies only on production thresholds: thus all particles are tracked down to zero range. In addition, Geant4 can ensure a consistent and material-independent accuracy of the simulation, as the production cuts are set in range, rather than in energy. The Tracking performs a correct treatment of near-boundary regions, based on the capability of processes to produce secondaries below threshold. The user can optionally define cuts in energy, path length and time-of-flight for special treatment of selected areas in the experimental set-up.

The Hits and Digi domains provide the functionality to reproduce the read-out structure of the detector and its electronic response, independently from the geometry used for the tracking.

A fast parameterisation framework is integrated with the full simulation, allowing independent and simplified detector descriptions and direct production of hits, at the same time ensuring a correct treatment near cracks. The fast simulation can be triggered according to various options, such as particle type, volume etc.

4. Geometry

The role of Geometry in Geant4 consists in providing the user the ability to describe the detailed geometrical structure of a detector; it also handles the equation of motion solvers in different fields and geometrical boundaries conditions for the propagation of particles. Geant4 Geometry provides an ISO STEP compliant solid modeller, allowing the exchange of models from CAD systems. Multiple solid representations, such as Constructive Solid Geometry, Boundary Represented Solids (including NonUniformRationalBSplines), Swept Solids, Boolean Operations, are supported according to the ISO STEP standard. A variety of integrators - beyond classical Runge-Kutta, including also multi-turn perturbative methods - allow a correct treatment of various fields of variable non-uniformity and differentiability. A proper integration is also performed to update the particle time of flight during transportation.

5. Geant4 physics

Geant4 Electromagnetic Physics manages lepton, γ, X-ray and optical photon, and muon interactions, as well as the electromagnetic interactions of hadrons and ions. It provides multiple implementations of ionization, Bremmstrahlung, multiple scattering, photoelectric effect (also with fluorescence), and Compton effect (also with polarization); it handles annihilation, pair conversion, synchrotron and transition radiation, scintillation, refraction, reflection, absorption and Raleigh effect. Low energy extensions - down to 250 eV for photons and electrons [10], as well as for hadrons [11] and ions [12] - are implemented, often provided with a variety of different models. The validity range of all the muon processes, based on theoretical models, scales up to the PeV region, allowing the simulation of ultra-high energy and cosmic ray physics.

Geant4 Hadronic Physics offers both parameterisation-driven models and a variety of theory-driven models, as well as treatment of low energy neutron transport. Parameterisation-driven models include high energy inelastic scattering, low energy inelastic and elastic scattering, fission, capture and dedicated processes for stopping kaons and pions. The theory-driven models provide two string parton models in the high energy regime (with the possibility to interface to Pythia7 [13] for the hard-scattering), as well as intra-nuclear transport models and pre-equilibrium, and a variety of deexcitation models, including evaporation, photo-evaporation, fission, Fermi break-up and multi-fragmentation. The low energy neutron transport is based on the best selections of all evaluated data available, exploiting the file system to maximise a granular and transparent access to the data sets for the user. Event biasing options, suitable, for instance, for radiation background studies, are provided. Lepton-hadron interactions, such as muon-nuclear interactions, photo-fission and general gamma-meson conversion are also implemented.

6. Other features

Particle Data Group compliant particle definitions - including hundreds of baryonic and mesonic resonances and ions, with their decay processes and modes - are available in the Toolkit.

A wide set of utilities, including a powerful set of random number generators, physics units and constants, as well as isotopes, elements, compounds definitions, interface to event generators and to ODBMS complete the Toolkit.

Extensive possibilities of interaction with the Geant4 system are offered to the user via a set of dedicated user-action classes.

Geant4 Visualisation and User Interface design, based on object oriented abstract interfaces, makes Geant4 independent from any particular graphics system. At the same time it allows multiple implementations of drivers for graphics systems and interaction with sophisticated GUIs or command line and batch systems. The implemented visualisation drivers support the use of X11, PostScript, OpenGL, OpenInventor, VRML and DAWN. The implemented user interfaces allow batch and interactive sessions based on command lines interfaces, as well as fully graphical user interface sessions, such as with OPACS or MOMO - the latter including automatic code generation for detector description and materials definition. The VRML2 driver also allows interactive picking of physics objects, such as tracks and hits, visualising in real time the associated physics information.

The ability to store relevant data in a persistent object store has been designed, developed and demonstrated in Geant4 for event data, hits and detector geometry descriptions.

7. Performance

A set of benchmarks [14] of Geant4 geometry navigation and tracking have shown that they are most performant even in complex geometries and faster than Geant3 [15]. Benchmarks [16] of Geant4 electromagnetic physics in realistic detector configurations, such as a calorimeter and thin silicon layers, have demonstrated that Geant4 is much faster than Geant3 in equivalent configurations, in addition providing better stability against cuts.

8. Experience of use of Geant4

Geant4 has been adopted by several experiments, space and medical applications as the basis for their simulations. Preliminary results have been reported [17], including also comparisons between test beam data [18] and Geant4-based simulation, showing a good agreement.

9. Conclusions

Geant4 is the result of the application of rigorous software engineering techniques to the domain of High Energy Physics.

Object-Oriented technology is a key factor in a world-wide distributed software development process. It also plays a fundamental role to allow abstract interfaces to software external to the Geant4 kernel - such as data bases for persistency, visualization libraries and user interfaces tools - without introducing dependencies.

The Geant4 design makes physics data, models and assumptions always transparently accessible to the user - rather than hard-coded in black-box packages, thus improving the verification and the reliability of simulation results.

The Geant4 software provides extensive physics capabilites, including a wide set of implementations of physics processes and models - that make the Geant4 toolkit suitable for applications in an ample variety of domains.

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