Introduction to Geant4

S. Hurtado

Servicio de Radioisótopos
Centro de Investigación, Tecnología e Innovación (CITIUS)
Sevilla SPAIN
What is GEANT4?

- Geant4, successor of GEANT3, is a public toolkit for HEP experiments using Object-Oriented environment and written in C++

- Geant4 is not only for HEP but cosmic rays physics, space science and medical applications.

- In order to meet such requirements a large degree of functionality and flexibility are provided for geometrical description, physics processes and visualization and analysis technologies.
The kernel

- Geant4 consists of 17 categories independently developed and maintained.

- Geant4 kernel:
  - Controls run, event, track, step, hit and trajectory.
  - Provides frameworks of geometrical modeling and physics processes.
Run

- Conceptually, a run (G4Run class) is a collection of events which share the same detector conditions.

- As an analogy of the real experiment, a run of Geant4 starts with “Beam On”

- Within a run, the user cannot change
  - detector geometry
  - settings of physics processes (*cross section tables are calculated according materials and cut-off values*)
  - But multiple runs in the same job with different geometries, materials etc.
Event

- At beginning of processing, an event contains primary particles (G4PrimaryGeneratorAction); these primaries are pushed into a stack
- When the stack becomes empty, processing of an event is over
- G4Event class represents an event; it has following objects at the end of its processing
  - List of primary vertexes and particles
  - Trajectory collection (optional)
  - Hits collections
  - Digits collections (optional)
Generating Primaries particles

- Interface to Event Generators
  - through ASCII file for generators supporting HEPEVT
  - abstract interface to Lund++
- Various utilities provided within the Geant4 Toolkit
  - Particle Gun
    - beam of selectable particle type, energy etc.
  - GeneralParticleSource
    - provides sophisticated facilities to model a particle source
    - used to model space radiation environments, sources of radioactivity in underground experiments etc.
  - you can write your own, inheriting from \textit{G4VUserPrimaryGeneratorAction}
- Particles
  - all PDG data
  - and more, for specific Geant4 use, like ions
**Hits and Digi**

- A sensitive detector creates hits using the information provided by the G4Step

- One can store various types of information in a hit
  - position and time of the step
  - momentum and energy of the track
  - energy deposition of the step
  - geometrical information
  - etc.

- A Digi represents a detector output
  - e.g. ADC/TDC count, trigger signal
- A Digi is created with one or more hits and/or other digits
Geometry

- CSG (Constructed Solid Geometries)
  - simple solids
- STEP extensions
  - polyhedra, spheres, cylinders, cones, toroids, etc.
- BREPS (Boundary REPresented Solids)
  - volumes defined by boundary surfaces
  - include solids defined by NURBS (Non-Uniform Rational B-Splines)

CAD exchange: ISO STEP interface

Fields: of variable non-uniformity and differentiability
Materials

- Different kinds of materials can be defined
  - isotopes (G4Isotope)
  - elements (G4Element)
  - molecules (G4Material)
  - compounds and mixtures (G4Material)

- Attributes associated:
  - temperature
  - pressure
  - state
  - density
Physics

- **Geant4 does not have any default particles or processes**
  - even for the particle transportation, one has to define it explicitly
- This is a *mandatory* and *critical* user’s task

- Derive your own concrete class from the G4VUserPhysicsList abstract base class
  - define all necessary particles
  - define all necessary processes and assign them to proper particles
  - define cuts (production thresholds in terms of range)
Data libraries

- Systematic collection and evaluation of experimental data from many sources worldwide

- Databases
  - ENDF/B, JENDL, FENDL, CENDL, ENSDF, JEF, BROND, EFF, MENDL, IRDF, SAID, EPDL, EEDL, EADL, SANDIA, ICRU etc.

- Collaborating distribution centres
  - NEA, LLNL, BNL, KEK, IAEA, IHEP, TRIUMF, FNAL, Helsinki, Durham, Japan etc.

- The use of evaluated data is important for the validation of physics results of the experiments
## Standard EM Physics

### 1 keV up to O(100 TeV)

<table>
<thead>
<tr>
<th>Phenomena</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gammas</strong></td>
<td></td>
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<tr>
<td></td>
<td>photo-electric effect</td>
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<tr>
<td></td>
<td>Compton scattering</td>
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<tr>
<td></td>
<td>electron, muon pair production</td>
</tr>
<tr>
<td><strong>Muons</strong></td>
<td></td>
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<tr>
<td></td>
<td>ionization</td>
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<td></td>
<td>bremsstrahlung</td>
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<tr>
<td></td>
<td>e+e- pair production</td>
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<tr>
<td><strong>Charged hadrons</strong></td>
<td></td>
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<tr>
<td></td>
<td>Ionization</td>
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<tr>
<td><strong>Electrons/Positrons</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ionization and delta ray production</td>
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<tr>
<td></td>
<td>Bremsstrahlung</td>
</tr>
<tr>
<td></td>
<td>e+e- annihilation</td>
</tr>
<tr>
<td></td>
<td>synchrotron radiation</td>
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<tr>
<td><strong>All charged particles</strong></td>
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<tr>
<td></td>
<td>multiple scattering</td>
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<td></td>
<td>transition radiation</td>
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<td></td>
<td>scintillation</td>
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<td>Cerenkov radiation</td>
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</tbody>
</table>
Low Energy Physics

\( e, \gamma \) down to 250/100 eV

EGS4, ITS to 1 keV

Geant3 to 10 keV

- Based on EPDL97, EEDL and EADL evaluated data libraries

- Hadron and ion models based on Ziegler and ICRU data and parameterisations
  - Atomic relaxation
    - (fluorescence and auger emission)

Gammas
- photo-electric effect
- Compton scattering
- Polarized Compton scattering
- Pair production
- Rayleigh scattering

Electrons/Positrons
- Ionization and delta ray production
- Bremsstrahlung

Charged hadrons and ions
- Ionization and delta ray production

PENELOPE Physics
Hadronic Physics

- Wide variety of models
  - the most complete hadronic simulation kit on the market
  - alternative and complementary models
  - it is possible to mix-and-match, with fine granularity
  - data-driven, parameterised and theoretical models

- Consequences for the users
  - no more confined to the black box of one package
  - the user has control on the physics used in the simulation, which contributes to the validation of experiment’s results

Parameterised and data-driven models based on experimental data

Theory-driven models

- Evaporation phase
- Low energy range, pre-equilibrium, O(100 MeV)
- Intermediate energy range, O(100 MeV) to O(5 GeV), intra-nuclear transport
- High energy range, hadronic generator régime
Radioactive Decay Module

- Handles $\alpha$, $\beta^-$, $\beta^+$, $\nu$ and anti-$\nu$, de-excitation $\gamma$-rays
  - can follow all the descendants of the decay chain
  - can apply variance reduction schemes to bias the decays to occur at user-specified times of observation

- Branching ratio and decay scheme data based on the Evaluated Nuclear Structure Data File (ENSDF)

- Applications:
  - underground background
  - backgrounds in spaceborne $\gamma$-ray and X-ray instruments
  - radioactive decay induced by spallation interactions
  - brachytherapy
  - etc.
Event Biasing

- Geant4 provides facilities for event biasing
- The effect consists in producing a small number of secondaries, which are artificially recognized as a huge number of particles by their statistical weights
- Event biasing can be used, for instance, for the transportation of slow neutrons or in the radioactive decay simulation
- Various variance reduction techniques available
Cuts per Region

- Geant4 has had a unique production threshold (‘cut’) expressed in length (i.e. minimum range of secondary), but energy cuts (particles are tracked down to a zero range/kinetic energy)
  - for all volumes
  - possibly different for each particle

New functionality

- enabling the tuning of production thresholds at the level of a sub-detector, i.e. region
- cuts are applied only for gamma, electron and positron, and only for processes which have infrared divergence

500 MeV/c proton in liq.Ar (4mm) / Pb (4mm) sampling calorimeter

Geant3 (energy cut) Ecut = 450 keV

Geant4 (range cut) Rcut = 1.5 mm corresponds to Ecut in liq.Ar = 450 keV
Ecut in Pb = 2 MeV
**User Interface**

- Two phases of user actions
  - setup of simulation
  - control of event generation and processing

- User Interface category separated from command interpreter
  - command-line (batch and terminal)
  - GUIs (X11/Motif, GAG, MOMO, OPACS, Java)

- Automatic code generation for geometry and physics through a GUI
  - GGE (Geant4 Geometry Editor)
  - GPE (Geant4 Physics Editor)
Visualization

- Control of several kinds of visualisation
  - detector geometry
  - particle trajectories
  - hits in the detectors

- Various drivers
  - OpenGL
  - OpenInventor
  - X11
  - Postscript
  - DAWN
  - OPACS
  - HepRep
  - VRML…
Analysis tools

- Through AIDA (Abstracts Interfaces for Data Analysis)
- Tools for analysis compliant with AIDA interfaces currently are:
  - Anaphe / PI
  - JAS
  - Open Scientist Lab
  - ROOT
### Performance

**GEANT4 v8.1 – SUSE Linux 10 – AMD Athlon 64 3700+**

<table>
<thead>
<tr>
<th>Geometry</th>
<th>particles</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ge crystal</td>
<td>40 keV-10^6</td>
<td>57.9</td>
</tr>
<tr>
<td></td>
<td>3000 keV-10^6</td>
<td>406.6</td>
</tr>
<tr>
<td>Ge detector + sample</td>
<td>40 keV-10^6</td>
<td>117.2</td>
</tr>
<tr>
<td></td>
<td>3000 keV-10^6</td>
<td>955.8</td>
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