Refresher Course

Geant 4

A Simulation Tool for Multi-disciplinary Applications

http://cern.ch/geant4/

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Based on the Refresher Course at IEEE NSS 2007
Geant 4

Born from the requirements of large scale HEP experiments

Widely used also in

- Space science and astrophysics
- Medical physics, nuclear medicine
- Radiation protection
- Accelerator physics
- Pest control, food irradiation
- Humanitarian projects, security
- etc.
- Technology transfer to industry, hospitals…

Most cited “Nuclear Technology” publication!
32 journals, >132000 papers
ISI Web of Science, 1990-2007
Technology transfer

Particle physics software aids space and medicine

Geant4 is a showcase example of technology transfer from particle physics to other fields such as space and medical science [...]...

CERN Courier, June 2002

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What is Geant 4?

OO Toolkit for the simulation of next generation HEP detectors

...of the current generation
...not only of HEP detectors

also...

An experiment of distributed software production and management

An experiment of application of rigorous software engineering methodologies and of the Object Oriented technology to the HEP environment

1st release: December 1998
2 new releases/year since then
Globalisation

Sharing requirements and functionality across diverse fields
Complex physics
Complex detectors
20 years
software life-span
From deep underground... ...to space

Dark matter and $\nu$ experiments

X and $\gamma$ astronomy, gravitational waves, radiation damage to components etc.

Cosmic ray experiments

Variety of requirements from diverse applications

Physics from the eV to the PeV scale

Detectors, spacecrafts and environment

For such experiments software is often mission critical

Require reliability, rigorous software engineering standards

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Medical Physics

from hospitals...

...to Mars

- Accurate modelling of radiation sources, devices and human body
- Precision of physics
- Reliability
- Easy configuration and friendly interface
- Speed

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in a fast changing computing environment

Start SPS 1976
W and Z observed 1983
Start LEP 1989
End LEP 2000

hardware, software, OS

...and don’t forget changes of requirements!

Evolution towards greater diversity we must anticipate changes

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A set of compatible components
- each component is specialised for a specific functionality
- each component can be refined independently to a great detail
- components can be integrated at any degree of complexity
- it is easy to provide (and use) alternative components
- the user application can be customised as needed

Openness to extension and evolution
- new implementations can be added w/o changing the existing code

Robustness and ease of maintenance protocols and well defined dependencies minimize coupling
The foundation

What characterizes Geant4

*Or:* the fundamental concepts, which all the rest is built upon
“It was noted that experiments have requirements for independent, alternative physics models. In Geant4 these models, differently from the concept of packages, allow the user to understand how the results are produced, and hence improve the physics validation. Geant4 is developed with a modular architecture and is the ideal framework where existing components are integrated and new models continue to be developed.”
Software Engineering plays a fundamental role in Geant4.

**User Requirements**
- formally collected
- systematically updated
- PSS-05 standard

**Software Process**
- spiral iterative approach
- regular assessments and improvements (SPI process)
- monitored following the ISO 15504 model

**Object Oriented methods**
- OOAD
- use of CASE tools
- openness to extension and evolution
- contribute to the transparency of physics
- interface to external software without dependencies

**Quality Assurance**
- commercial tools
- code inspections
- automatic checks of coding guidelines
- testing procedures at unit and integration level
- dedicated testing team

**Use of Standards**
- de jure and de facto
The functionality

What Geant4 can do
How well it does it
The kernel

Run and event
- Multiple events
  - possibility to handle the pile-up
- Multiple runs in the same job
  - with different geometries, materials etc.
- Powerful stacking mechanism
  - three levels by default: handle trigger studies, loopers etc.

Tracking
- Decoupled from physics
  - all processes handled through the same abstract interface
- Independent from particle type
- New physics processes can be added to the toolkit without affecting tracking

Geant4 has only production thresholds, no tracking cuts
- all particles are tracked down to zero range
- energy, TOF ... cuts can be defined by the user

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Geometry

- **Role**
  - detailed detector description
  - efficient navigation

- **Three conceptual layers**
  - **Solid**: shape, size
  - **LogicalVolume**: material, sensitivity, daughter volumes, etc.
  - **PhysicalVolume**: position, rotation

- One can do fancy things with geometry…

Boolean operations

Transparent solids

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Solids

Multiple representations
Same abstract interface

- CSG (Constructed Solid Geometries)
  - simple solids

- STEP extensions
  - polyhedra, spheres, cylinders, cones, toroids, etc.

- BREPS (Boundary REPpresented Solids)
  - volumes defined by boundary surfaces

CAD exchange
Physical Volumes

Versatility to describe complex geometries

 placement

parameterised

replica

assembled

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Electric and magnetic fields of variable non-uniformity and differentiability

Geant4 field ~ 2 times faster than FORTRAN/GEANT3

1 GeV proton in the Earth’s geomagnetic field

Courtesy of M. Stavrianakou for the CMS Collaboration

Courtesy Laurent Desorgher, University of Bern

MOKKA
Linear Collider Detector

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Not only large scale, complex detectors….

Analytical breast

Voxel breast

simple geometries

small scale components

Geant4 anthropomorphic phantoms

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You may also do it wrong...

Tools to detect badly defined geometries

Geant4 Macro:

```cpp
/vis/scene/create
/vis/sceneHandler/create VRML2FILE
/vis/viewer/create
/olap/goto ECalEnd
/olap/grid 7 7 7
/olap/trigger
/vis/viewer/update
```

Output:

```
delta=59.3416
vol 1; point=(560.513,1503.21,-141.4)
volution 2: point=(560.513,1443.86,-141.4)
A -> B:
 [0]: ins=[2] PVName=[NewWorld;0] Type=[N] ...
 [1]: ins=[0] PVName=[ECalEndcap0] Type=[N] ...
 [2]: ins=[1] PVName=[ECalEndcap07;38] Type=[N] ...
B -> A:
 [0]: ins=[2] PVName=[NewWorld;0] Type=[N] ...
```

red: mother
blue: daughters
daughters are protruding their mother

NavigationHistories of points of overlap (including: info about translation, rotation, solid specs)
Abstract interface to physics processes

- Tracking independent from physics
- Uniform treatment of electromagnetic and hadronic processes

Distinction between processes and models

- multiple models for the same physics process
  (complementary/alternative)

Transparency (supported by encapsulation and polymorphism)

- Calculation of cross-sections independent from the way they are accessed
  (data files, analytical formulae etc.)
- Calculation of the final state independent from tracking

Explicit use of units throughout the code

Open system

- Users can easily create and use their own models
Electromagnetic physics

- electrons and positrons
- \( \gamma \), X-ray and optical photons
- muons
- charged hadrons
- ions

Comparable to Geant3 already in the \( \alpha \) release (1997)
Further extensions (facilitated by the OO technology)

High energy extensions
- needed for LHC experiments, cosmic ray experiments…

Low energy extensions
- fundamental for space and medical applications, dark matter and \( \nu \) experiments, antimatter spectroscopy etc.

Alternative models for the same process

All obeying to the same abstract Process interface transparent to tracking

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Calorimetry

Single crystal containment: $E_{1x1}/E_{3x3}$ versus position

Data
G4

Courtesy of M. Stavrianakou for the CMS Collaboration

Tracking

Geant4
Standard
Electromagnetic
Physics

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**Barkas effect** (charge dependence)

**Hadron and ion** models based on Ziegler and ICRU data and parameterisations

1. Based on EPDL97, EEDL and EADL evaluated data libraries
2. Based on Penelope analytical models

**Geant4**

- $e, \gamma$ down to 250/100 eV
- EGS4, ITS to 1 keV
- Geant3 to 10 keV

**Atomic relaxation**

- Fluorescence
- Auger effect

**Bragg peak**

- Shell effects
- $e, \gamma$ down to 250/100 eV
- EGS4, ITS to 1 keV
- Geant3 to 10 keV

**Hadron and ion** models based on Ziegler and ICRU data and parameterisations

- Based on Penelope analytical models

**Figure 8**: Ion electronic stopping power in aluminium. Points - the best fit on the data from Ref. [12], solid line - GEANT4's parametrisation. The accuracy of the data is about 5%.
“Comparison of Geant4 electromagnetic physics models against the NIST reference data”


Geant4 electromagnetic physics models are accurate
Compatible with NIST data within NIST accuracy (LowE p-value > 0.9)

Mass attenuation coefficient in Fe

Results
All Geant4 models compatible with NIST
Best agreement:
Geant4 LowE models

H₀ REJECTION AREA
A medical accelerator for IMRT

**Kolmogorov-Smirnov test**

<table>
<thead>
<tr>
<th>range</th>
<th>D</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>-84 (\div) -60 mm</td>
<td>0.385</td>
<td>0.23</td>
</tr>
<tr>
<td>-59 (\div) -48 mm</td>
<td>0.27</td>
<td>0.90</td>
</tr>
<tr>
<td>-47 (\div) 47 mm</td>
<td>0.43</td>
<td>0.19</td>
</tr>
<tr>
<td>48 (\div) 59 mm</td>
<td>0.30</td>
<td>0.82</td>
</tr>
<tr>
<td>60 (\div) 84 mm</td>
<td>0.40</td>
<td>0.10</td>
</tr>
</tbody>
</table>
Dosimetry in interplanetary missions

Aurora Programme

Dose in astronaut resulting from Galactic Cosmic Rays

GCR - EM Physics - 10 cm polyethylene

Dose in the phantom

Depth in the phantom

Gray

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Solar system explorations

Study of the elemental composition of planets, asteroids and moons clues to solar system formation

X-ray fluorescence

Arising from the solar X-ray flux, sufficient, for the inner planets, to significant fluorescence fluxes to an orbiter

PIXE

Significant only during particle events, during which it can exceed XRF

Anderson-Darling GoF test

$A_c (95\%) = 0.752$

Fluorescence spectrum from Hawaiian basalt: experimental data and simulation
Detection of Landmines using Radiation Based Techniques

Geant4 User’s Workshop, SLAC 2002 02 21

Dr Anthony A. Faust
Threat Detection Group
Defence Research Establishment Suffield

X-ray Backscatter Imaging

- Exploit $Z$ dependent differences in Compton/Photoelectric cross-sections
- $Z_{\text{mine}}^{\text{eff}} \sim 8$ and $Z_{\text{soil}}^{\text{eff}} \sim 14$

Used Low Energy packages

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Polarisation

Cross section:
\[
\frac{d\sigma}{d\Omega} = \frac{1}{2} r_0^2 \frac{h \nu^2}{h \nu_0^2} \left[ \frac{h \nu_0}{h \nu} + \frac{h \nu}{h \nu_0} - 2 \sin^2 \theta \cos^2 \phi \right]
\]

Sample Methods:
- Sample \(\theta\)
- \(\theta\) - Energy Relation \(\Rightarrow\) Energy
- Sample of \(\phi\) from \(P(\phi) = a(b - c \cos^2 \phi)\) distribution

\[
\cos \xi = \sin \theta \cos \phi \quad \Rightarrow \quad \sin \xi = \sqrt{1 - \sin^2 \theta \cos^2 \phi} = N
\]

Scattered Photon Polarization

\[
\vec{\varepsilon}_\perp = \frac{1}{N} \left( \cos \theta \hat{j} - \sin \theta \sin \phi \hat{k} \right) \sin \beta
\]

\[
\vec{\varepsilon}_\parallel = \left( \hat{N} - \frac{1}{N} \sin^2 \theta \sin \phi \cos \phi \hat{j} - \frac{1}{N} \sin \theta \cos \theta \cos \phi \hat{k} \right) \cos \beta
\]

Low Energy
Polarised Compton

250 eV - 100 GeV

Theta Polar angle
Ph Azimuthal angle
\(\varepsilon\) Polarization vector

Sample Methods:

Integrating over \(\phi\)

Cross section:

\[
\frac{d\sigma}{d\Omega} = \frac{1}{2} r_0^2 \frac{h \nu^2}{h \nu_0^2} \left[ \frac{h \nu_0}{h \nu} + \frac{h \nu}{h \nu_0} - 2 \sin^2 \theta \cos^2 \phi \right]
\]

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**γ astrophysics**

**γ-ray bursts**

Typical telescope:
- Tracker
- Calorimeter
- Anticoincidence

- γ conversion
- electron interactions
- multiple scattering
- δ-ray production
- charged particle tracking

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Muons

- 1 keV up to 10 PeV scale
- Simulation of ultra-high energy and cosmic ray physics
- High energy extensions based on theoretical models

- Muon Muon energy loss
- Muon radiation processes
- Gamma conversion to muon pair
- Positron annihilation to muon pair
- Positron annihilation into hadrons
Optical photons

Production of optical photons in HEP detectors is mainly due to Cherenkov effect and scintillation.

Processes in Geant4:
- in-flight absorption
- Rayleigh scattering
- medium-boundary interactions (reflection, refraction)

Geant4 Optical Processes:
Scintillating Cells and WLS Fibers

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Courtesy of J. Mc Cormick (SLAC)
Milagro is a Water-Cherenkov detector located in a 60m x 80m x 8m covered pond near Los Alamos, NM.

<table>
<thead>
<tr>
<th>Aerogel Thickness</th>
<th>Yield Per Event</th>
<th>Cherenkov Angle mrad</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 cm DATA</td>
<td>6.3 ± 0.7</td>
<td>247.1±5.0</td>
</tr>
<tr>
<td>4 cm MC</td>
<td>7.4 ± 0.8</td>
<td>246.8±3.1</td>
</tr>
<tr>
<td>8 cm DATA</td>
<td>9.4 ± 1.0</td>
<td>245.4±4.8</td>
</tr>
<tr>
<td>8 cm MC</td>
<td>10.1 ± 1.1</td>
<td>243.7±3.0</td>
</tr>
</tbody>
</table>
prompt scintillation

ZEPLIN III
Dark Matter Detector

signal in PMT

termoluminescence

GEANT4 Scintillation Event in BOREXINO

Courtesy of H, Araujo, Imperial College London

Courtesy of Borexino
Hadronic physics

- Completely different approach w.r.t. the past (Geant3)
  - native
  - transparent
  - no longer interface to external packages
  - clear separation between data and their use in algorithms

- Cross section data sets
  - transparent and interchangeable

- Final state calculation
  - models by particle, energy, material

- Ample variety of models
  - the most complete hadronic simulation kit on the market
  - alternative and complementary models
  - data-driven, parameterised and theoretical models
Parameterised and data-driven hadronic models (1)

Based on experimental data

- Some models originally from GHEISHA
  - completely reengineered into OO design
  - refined physics parameterisations
- New parameterisations
  - pp, elastic differential cross section
  - nN, total cross section
  - pN, total cross section
  - np, elastic differential cross section
  - πN, total cross section
  - πN, coherent elastic scattering

p elastic scattering on Hydrogen
Parameterised and data-driven hadronic models (2)

Other models are completely new, such as:

- **Stopping particles**: $\pi^-$, $K^-$
  (relevant for $\mu/\pi$ PID detectors)

- All worldwide existing databases used in neutron transport:
  Brond, CENDL, EFF, ENDFB, JEF, JENDL, MENDL etc.

- Neutrons

- $\gamma$s from 14 MeV neutron capture on $U_r$
Theory-driven models

- Complementary and alternative models
- **Evaporation phase**
- Low energy range: $O(100 \text{ MeV})$: *pre-equilibrium*
- Intermediate energy range, $O(100 \text{ MeV})$ to $O(5 \text{ GeV})$: *intra-nuclear transport*
- High energy range: *hadronic generator* régime

![Bertini cascade model: pion production from 730 MeV proton on Carbon](image1)

![G4QGSModel: differential pion yields in pion-Mg](image2)
The two worlds can be mixed...

**Photon evaporation - Sn(50,112), 80 MeV**

Discrete transitions from ENSDF

**Gran Sasso National Laboratory**

$^{60}\text{Co}$

Environmental analysis of Abruzzo geological composition
Other components

- **Materials**
  - elements, isotopes, compounds, chemical formulae

- **Particles**
  - all PDG data
  - and more, for specific Geant4 use, like ions

- **Hits & Digi**
  - to describe detector response

- **Primary event generation**
  - some general purpose tools provided within the Toolkit
    - eg. GeneralParticleSource

- ...and much more (no time to mention all!)

---

read-out geometry  
event biasing  
fast simulation  
parallelisation  
persistency  
much more physics  

etc.

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Fast simulation

- Geant4 allows to perform full simulation and fast simulation in the same environment
- Geant4 parameterisation produces a direct detector response, from the knowledge of particle and volume properties
  - hits, digis, reconstructed-like objects (*tracks*, *clusters* etc.)
- Great flexibility
  - activate fast/full simulation **by detector**
    *example:* full simulation for inner detectors, fast simulation for calorimeters
  - activate fast/full simulation **by geometry region**
    *example:* fast simulation in central areas and full simulation near cracks
  - activate fast/full simulation **by particle type**
    *example:* in e.m. calorimeter, e/γ parameterisation + full simulation of hadrons
  - parallel geometries in fast/full simulation
    *example:* inner and outer tracking detectors distinct in full simulation, but handled together in fast simulation
Interface to external tools in Geant4

Through abstract interfaces
- no dependence
- minimize coupling of components

Similar approach
- Visualisation
- (G)UI
- Persistency
- Analysis

The user is free to choose the concrete system he/she prefers for each component

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User Interface

- Several implementations, all handled through abstract interfaces
- Command-line (batch and terminal)
- GUls
  - X11/Motif, GAG, MOMO, OPACS, Java

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

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

- Various drivers
  - OpenGL
  - OpenInventor
  - X11
  - Postscript
  - DAWN
  - OPACS
  - HepRep
  - VRML...

- All handled through abstract interfaces
Pushing Geant4 to the limit
Heavy ion beams

CMS

Events with > 50000 particles/event in detector acceptance

~ 180 minutes to simulate 1 event with 55K generator tracks

Medical ion beam

Geant4 simulation

Beam Track Reconstruction 135 MeV/u $^{12}$C beam

NIRS N. Kanematsu, M. Komori - Nagoya K. Niwa, T. Toshito, T. Nakamura, T. Ban, N. Naganawa, S. Takahashi - Uchu-ken

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LISA (gravitational waves)

Geant4 relevant for evaluation of space charging effects

Very long base-line: 1 million km
Very high precision: < 1nm – 1pm (!)

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Courtesy H. Araujo, A. Howard, IC London
Access to distributed computing

DIANE

Transparent access to a distributed computing environment

Parallelisation

Access to the GRID

- Local computing farm
- Geographically distributed grid
Traceback from a run on CrossGrid testbed

Current #Grid setup (computing elements):
5000 events, 2 workers, 10 tasks (500 events each)

Resource broker running in Portugal

matchmaking CrossGrid computing elements

- aocegrid.uab.es:2119/jobmanager-pbs-workq
- bee001.ific.uv.es:2119/jobmanager-pbs-qgrid
- cgnode00.di.uoa.gr:2119/jobmanager-pbs-workq
- cms.fuw.edu.pl:2119/jobmanager-pbs-workq
- grid01.physics.auth.gr:2119/jobmanager-pbs-workq
- xg001.inp.demokritos.gr:2119/jobmanager-pbs-workq
- xgrid.icm.edu.pl:2119/jobmanager-pbs-workq
- zeus24.cyf-kr.edu.pl:2119/jobmanager-pbs-infinite
- zeus24.cyf-kr.edu.pl:2119/jobmanager-pbs-long
- zeus24.cyf-kr.edu.pl:2119/jobmanager-pbs-medium
- zeus24.cyf-kr.edu.pl:2119/jobmanager-pbs-short
- ce01.lip.pt:2119/jobmanager-pbs-qgrid
Is it worthwhile?
Comparison with commercial radiotherapy treatment planning systems

M. C. Lopes, L. Peralta, P. Rodrigues, A. Trindade
IPOFG-CROC Coimbra Oncological Regional Center
LIP - Lisbon

CT-simulation with a Rando phantom
Experimental data with TLD LiF dosimeter

CT images used to define the geometry:
a thorax slice from a Rando anthropomorphic phantom

\[ \chi^2 / \text{ndf} (\text{GEANT 4}) = 0.52 \]
\[ \chi^2 / \text{ndf} (\text{TMS}) = 0.81 \]
\[ \chi^2 / \text{ndf} (\text{PLATO}) = 6.71 \]

Central-Axis depth dose

Profile curves at 9.8 cm depth

PLATO overestimates the dose at ~ 5% level
Robustness

BaBar Simulation Production

BaBar simulation production – a millennium of work in under a year.


IEEE 2004 - Oct. 21, 2004

Data Challenges in LHC experiments
The **Geant 4** kit

- **Code**
  - ~1M lines of code
  - continuously growing
  - publicly downloadable from the web

- **Documentation**
  - 5 manuals
  - publicly available from the web

- **Examples**
  - distributed with the code
  - various complete applications of (simplified) real-life experimental set-ups

- **Platforms**
  - Linux, SUN, Windows, (MacOS)

- **Commercial software**
  - None required
  - Can be interfaced

- **Free software**
  - CVS
  - gmake, g++
  - CLHEP

- **Graphics & (G)UI**
  - OpenGL, X11, OpenInventor, DAWN, VRML...
  - OPACS, GAG, MOMO...

- **Persistency**
  - it is possible to run in transient mode
  - in persistent mode use a HepDB interface, ODMG standard
The next frontier

The power of abstract interfaces
Simulation of Interactions of Radiation with Biological Systems at the Cellular and DNA Level

Estimating cancer risk for human exposures to space radiation is a challenge which involves a wide range of knowledge in physics, chemistry, biology and medicine.

Traditionally, the biological effects of radiation are analysed in top-bottom order, i.e. evaluation of the absorbed macroscopic radiation dose at a given location in the biological tissue is translated to the degree of danger it presents, and dose limits are consequently set that are considered to be acceptable.

A novel approach, based on the new-generation object-oriented Geant4 Monte Carlo Toolkit, proceeds in a reverse order, from bottom to top, by analysing the nano-scale effects of energetic particles at the cellular and DNA molecule level.

This project is sponsored by the European Space Agency (ESA) and is pursued by a multidisciplinary European team of biologists, physicians, physicists, space scientists and software engineers.
Conclusions
Complexity of physics, detectors, environments
A rapidly changing computing environment
Similar requirements across diverse fields (HEP, astrophysics, medicine…)

The response:
- rigorous approach to software engineering
- OO technology
- powerful functionality, rich physics

Achieve:
- openness to extension and evolution
- maintainability over an extended time scale
- transparency of physics

Results:
- HEP, space science, medical physics…
- science + technology transfer