The **Geant 4** Simulation Toolkit

and its applications to medical and space science

Maria Grazia Pia
INFN Genova, Italy


for the Geant4 Collaboration

...with contributions from many **Geant 4** users

VIII Simulation Symposium
Hayama, 3-7 September 2001
What is **Geant 4**?

**OO Toolkit for the simulation of next generation HEP detectors**
...of the current generation too
...not only of HEP detectors

also...

An experiment of distributed software production and management

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

Born from the requirements of large scale HEP experiments

Geant3

- Fortran
- CERN product

inadequate for LHC experiments

1st release: December 1998
2 new releases/year since then
Geant 4

- Run, event and track management
- PDG-compliant particle management
- Geometry and materials
- Tracking
- **Physics processes**
- Detector response
- User interface
- Visualisation
- Persistency

Code and documentation publicly distributed from www

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Geant4 Collaboration

Development, maintenance, distribution, user support of the Geant4 Toolkit

Laboratories
CERN, TJNL, KEK, SLAC, TRIUMF

Agencies
European Space Agency (ESA)

National Institutes
INFN (Italy), IN2P3 (France), PPARC (UK)

Research Institutes
Karolinska (Stockholm), LIP (Lisbon)
Lebedev (Moscow), Serpukov (Protvino), Budker (Novosibirsk)

Universities
Barcelona (Spain), Cordoba (Argentina), Frankfurt (Germany), Helsinki (Finland), Northeastern (USA) etc.

Governed by a Memorandum of Understanding among the member parties

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ATLAS
27km circumference
~100m deep

LHC

ALICE

Storage
Raw recording rate 0.1–1 GByte/s
Accumulating at 5-8 PBytes/year

Complex physics, complex detectors…

Processing
200,000 of today’s fastest PCs
...in a fast changing computing environment

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

Evolution towards greater diversity we must anticipate changes
Guidelines for physics

From the Minutes of LCB (LHCC Computing Board) meeting on 21 October, 1997:

“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.”

Physics in Geant4

Rich of diverse models  Transparent  Open to evolution

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**OO technology**

- Openness to **extension** and **evolution**
  - new implementations can be added w/o changing existing code
- Robustness and ease of **maintenance**
  - **protocols** and well defined dependencies minimise coupling

**Strategic vision**

**Toolkit**

- A set of compatible components
  - each component is **specialised** for a specific functionality
  - each component can be **refined** independently to 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
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
- monitored following the ISO 15504 model

Object Oriented methods:
- OOAD
- use of CASE tools
- essential for distributed parallel development
- contribute to the transparency of physics
- commercial tools
- code inspections
- automatic checks of coding guidelines
- testing procedures at unit and integration level
- dedicated testing team

Quality Assurance:
- de jure and de facto

Use of Standards:
- de jure and de facto
Geant4 in LHC experiments

A few examples of usage...

Geant4 is definitively a mature and useful product for large scale detector response simulations!

P. Loch (ATLAS experiment), Calor 2002 Conference

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Globalisation

Sharing requirements and functionality across diverse fields
Requirements for LowE protons in Geant 4

GEANT4 LOW ENERGY ELECTROMAGNETIC PHYSICS

User Requirements Document

Status: in CVS repository

Version: 2.4
Project: Geant4-LowE
Reference: LowE-URD-V2.4
Created: 22 June 1999
Last modified: 26 March 2001
Prepared by: Petteri Nieminen (ESA) and Maria Grazia Pia (INFN)

- **UR 2.1** The user shall be able to simulate electromagnetic interactions of positive charged hadrons down to $E < 1$ KeV.

  - **Need:** Essential
  - **Priority:** Required by end 1999
  - **Stability:** T. b. d.
  - **Source:** Medical physics groups, PIXE
  - **Clarity:** Clear
  - **Verifiability:** Verified

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Geant 4 LowE Hadrons and ions

OOAD...
...and validation

Experimental data:
Bragg peak

- data
- simulation

INFN-Torino medical physics group

Test set-up at PSI

Courtesy of R. Gotta, Thesis

Geant4 LowE Working Group
What could be the source of detector damage?

- Radiation belt electrons?
- Scattered in the mirror shells?
- Effectiveness of magnetic “brooms”?
- Electron damage mechanism? - NIEL?
- Other particles? Protons, cosmics?

Analysis of ACIS calibration source data from the last 5 days has shown an unexplained degradation in the energy resolution of the front-side illuminated CCD chips of ACIS. The degradation is evident in data starting from 5 days ago and shows a change in the FWHM from approx 130 eV to 500 eV.

Operations CXO Status Report
Friday 9/10/99 10:00am EST
Low-E (~100 keV to few MeV), low-angle (~0°-5°) proton scattering
What happened next?

XMM was launched on 10 December 1999 from Kourou

XXM-Newton

EPIC image of the two flaring Castor components and the brighter YY Gem

Courtesy of R. Nartallo, ESA

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...and the other way round
Low energy $e, \gamma$ extensions

...were triggered by astrophysics requirements

**X-Ray Surveys of Planets, Asteroids and Moons**

Induced X-ray line emission: indicator of target composition (~100 $\mu$m surface layer)

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Courtesy ESA Space Environment & Effects Analysis Section
Low Energy Processes: $e, \gamma$

250 eV up to 100 GeV

New electromagnetic physics models

Based on EPDL97, EEDL and EADL evaluated data libraries

Validation: comparison with NIST Natl. Inst. Cancer Research

Photon attenuation coefficient

- Geant4
- NIST
...the first user application

Exploiting X-ray fluorescence to lower the energy spectrum of photons (and electrons) and enhance the RBE

10 keV electron in water

R. Taschereau, R. Roy, J. Pouliot

Centre Hospitalier Universitaire de Quebec, Dept. de radio-oncologie, Canada
Univ. Laval, Dept. de Physique, Canada
Univ. of California, San Francisco, Dept. of Radiation Oncology, USA

Terrisol

Distance (nm)
Bepi Colombo
ESA mission to Mercury

Analysis of the elemental composition of Mercury crust through X-ray spectroscopy

Fluorescent spectrum of Icelandic Basalt ("Mars-like")

Experimental data:
courtesy of A. Owens, ESA
6.5 keV photon beam, BESSY

Anderson-Darling goodness of fit test on various data sets: compatibility 95% CL
Back to HEP...

- Similar **requirements** on low energy physics from underground HEP experiments ~1 year later

- Recent interest on these physics models from LHC for precision detector simulation

**UKDM, Boulby Mine**

**Credit:** O. Cremonesi, INFN Milano

** Courtesy of H. Araujo and A. Howard, IC London**
Medical Applications

Verification of conventional radiotherapy treatment planning (as required by protocols)

Investigation of innovative methods in radiotherapy

Radiodiagnostics
What in **Geant 4** is relevant to the bio-medical community?

- Advanced **functionalities in geometry, physics, visualisation etc.**
- Specific facilities controlled by a friendly **UI**
- Extensibility to accommodate new user requirements
- **Transparency of physics**
- **User support from experts**
- Adoption of **standards wherever available (de jure or de facto)**
- **A rigorous software process**
- Quality Assurance based on sound software engineering
- Independent validation by a large user community worldwide
- Use of **evaluated data libraries**

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shell effects

Physics requirements

Many new physics features w.r.t. Geant3

\( e, \gamma \) down to 250 eV
(EGS4, ITS to 1 keV, Geant3 to 10 keV)

Based on EPDL97, EEDL and EADL evaluated data libraries

And much more:
- fluorescence
- radioactive decay
- hadronic models
- etc...

And much relevant functionality in other domains too, not only physics!

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Endocavitary brachytherapy

Radioactive sources are used to deposit therapeutic doses near tumors, while preserving surrounding healthy tissues.

Source anisotropy

Plato-BPS treatment planning algorithm makes some crude approximation ($\phi$ dependence, no radial dependence).

Precise dose distribution with Geant4

MicroSelectron-HDR Ir-192 source
Superficial brachytherapy

No commercial treatment planning software available

Leipzig applicators

Experimental validation:
- Geant4
- Nucletron data
- IST data
Interstitial brachytherapy

Bebig Isoseed I-125 source

Isodose curves

0.16 mGy = 100%

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RBE enhancement of a $^{125}$I brachytherapy seed with characteristic X-rays from its constitutive materials

Goal: improve the biological effectiveness of titanium encapsulated $^{125}$I sources in permanent prostate implants by exploiting X-ray fluorescence

Titanium shell (50 µm)
Silver core (250 µm)
4.5 mm

Distance away from seed

RBE

Mo-Y
M200

++ tumors
-- healthy tissues

39 ≤ Z ≤ 45
20 µm thick
... up to 300 µm

All the seed configurations modeled and simulated with Geant4

R. Taschereau, R. Roy, J. Pouliot
Centre Hospitalier Universitaire de Québec, Dépt. de radio-oncologie, Canada
Univ. Laval, Dépt. de Physique, Canada
Univ. of California, San Francisco, Dept. of Radiation oncology, USA

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Validation of phase-space distributions from a Siemens KD2 linear accelerator at 6 MV photon mode.
Comparison with commercial treatment planning systems

M. C. Lopes ¹, L. Peralta ², P. Rodrigues ², A. Trindade ²
¹ IPOFG-CROC Coimbra Oncological Regional Center - ² LIP - Lisbon

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

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

Central-Axis depth dose

Deviation at ~6 cm identified as an experimental problem

Profile curves at 9.8 cm depth
PLATO overestimate the dose at ~ 5% level

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A more complex set-up

M. C. Lopes\textsuperscript{1}, L. Peralta\textsuperscript{2}, P. Rodrigues\textsuperscript{2}, A. Trindade\textsuperscript{2}
\textsuperscript{1} IPOFG-CROC Coimbra Oncological Regional Center - \textsuperscript{2} LIP - Lisbon

An off-axis depth dose taken at one of the slices near the isocenter

PLATO fails on the air cavities and bone structures and cannot predict accurately the dose to tissue that is surrounded by air

Deviations are up to 25-30%
Other medical applications

- IORT (INFN Cosenza)
- Metabolic therapy (INFN Cosenza)
- IMRT (IRCC Candiolo)
- Design and optimisation of treatment heads
- Hadron therapy
- PET (GATE - ClearPET)
- etc.

no time to mention all...
Space Applications

Astronomy and astrophysics
Fundamental physics

Effects of the space radiation environment
(shielding)

Effects on manned missions
Space radiation environment

Photons: \[300 \text{ eV} < E < 20 \text{ MeV}\]
Electrons: \[10 \text{ keV} < E < 20 \text{ MeV}\]
Protons: \[10 \text{ keV} < E < 20 \text{ MeV}\]
Ions: \[10 \text{ keV} < E < 20 \text{ MeV}\]

Galactic and extra-galactic cosmic rays

Solar X-rays

Induced emission

Trapped particles

Solar flare neutrons and \(\gamma\)-rays

Anomalous cosmic rays

Jovian electrons

Solar flare electrons, protons, and heavy ions
Modules for space applications

- General purpose source particle module
- Delayed radioactivity
- INTEGRAL and other science missions
- Low-energy e.m. extensions
- Geological surveys of solar system
- Instrument design purposes

**Geant 4**

- CAD tool front-end
- Sector Shielding Analysis Tool
- Dose calculations

**GeMAT**
Geant4-based Microdosimetry Analysis Tool

**MULASSIS**
MUlti-LAyer Shielding Simulation Software
γ astrophysics

γ-ray bursts

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

Typical telescope:
Tracker
Calorimeter
Anticoincidence

BeppoSAX Observation of Gamma-Ray Burst on February 28, 1997

GLAST

AGILE

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Polarised Gamma Astrophysics

Compton astrophysics
(MeV region)

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

- $\theta$ Polar angle
- $\phi$ Azimuthal angle
- $\varepsilon$ Polarization vector

Geant 4

G4LowEnergyPolarizedCompton
LISA (gravitational waves)

Geant4 relevant for evaluation of space charging effects

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

Courtesy of H. Araujo, A. Howard, IC London
Geant 4 - DNA

Study of radiation damage at the cellular and DNA level in the space radiation environment (and other applications...)

Multi-disciplinary Collaboration of
- astrophysicists/space scientists
- particle physicists
- medical physicists
- computer scientists
- biologists
- physicians

5.3 MeV α particle in a cylindrical volume
The inner cylinder has a radius of 50 nm

Relevance for space: astronaut and airline pilot radiation hazards, biological experiments
Also in radiotherapy, radiobiology...

http://www.ge.infn.it/geant4/dna/
Geant4 is a showcase example of technology transfer from particle physics to other fields such as space and medical science […].

CERN Courier, June 2002

http://cern.ch/geant4/
http://www.cern.ch/geant4-tt/
http://www.ge.infn.it/geant4/
Maria.Grazia.Pia@cern.ch or pia@ge.infn.it

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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
Thanks!

- CERN (J. Knobloch)
- ESA/ESTEC (R. Nartallo, P. Nieminen, A. Owens, A. Peacock)
- Imperial College, London (H. Araujo, A. Howard)
- INFN Cosenza (F. Castrovillari, D. Cupe, E. Lamanna)
- INFN LNS (G.A.P. Cirrrone, G. Cuttone)
- INFN Torino (S. Chauvie, R. Gotta, F. Marchetto, V. Rolando, A. Solano)
- IST (S. Agostinelli, F. Foppiano, S. Garelli, S. Guatelli, M. Tropeano)
- Univ. Laval, Quebec (L. Beaulieu, J.F. Carriere, R. Taschereau)
- LIP (L. Peralta, P. Rodrigues, A. Trindade)
- PSI (N. Crompton, P. Juelke)
- Savona Hospital (G. Ghiso, R. Martinelli)
- Geant4 Collaboration
- Geant4 users (too many to mention them all...)
- The Simulation Symposium Organizers
- Katsuya Amako (KEK)