Simulations in Radiation Therapy and medical physics

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Planning et objectifs

- DQPRM 2ème année – promo 2024-2026
- Simulations Monte-Carlo en radiothérapie (TC 1.5)

- 28 Janvier 2025
    - 10h – 12h: cours, salle A1
    - 13h30 – 16h30: TD salle info (146-148)
- 29 Janvier 2025
    - 9h – 12h et 13h30 – 16h30 : TD salle info (146-148)

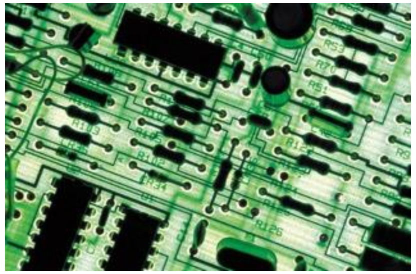
- Introduction GATE et prise en main

DQPRM 2025 - PDF

https://128.pl/ONcIf

Simulations in Medical Physics

- What ? Numerical model, computer
- Why ? To predict, to analyse, to reduce the nb of measurements
- When ? 100% treatment, 100% design imaging systems
- Who ? MedPhys in clinic, industrial, research
- Where ? Hospital, labs, industry ; RT and NM ; maybe Radiology
- How ? Design simulation. Run. Analyse. Redo

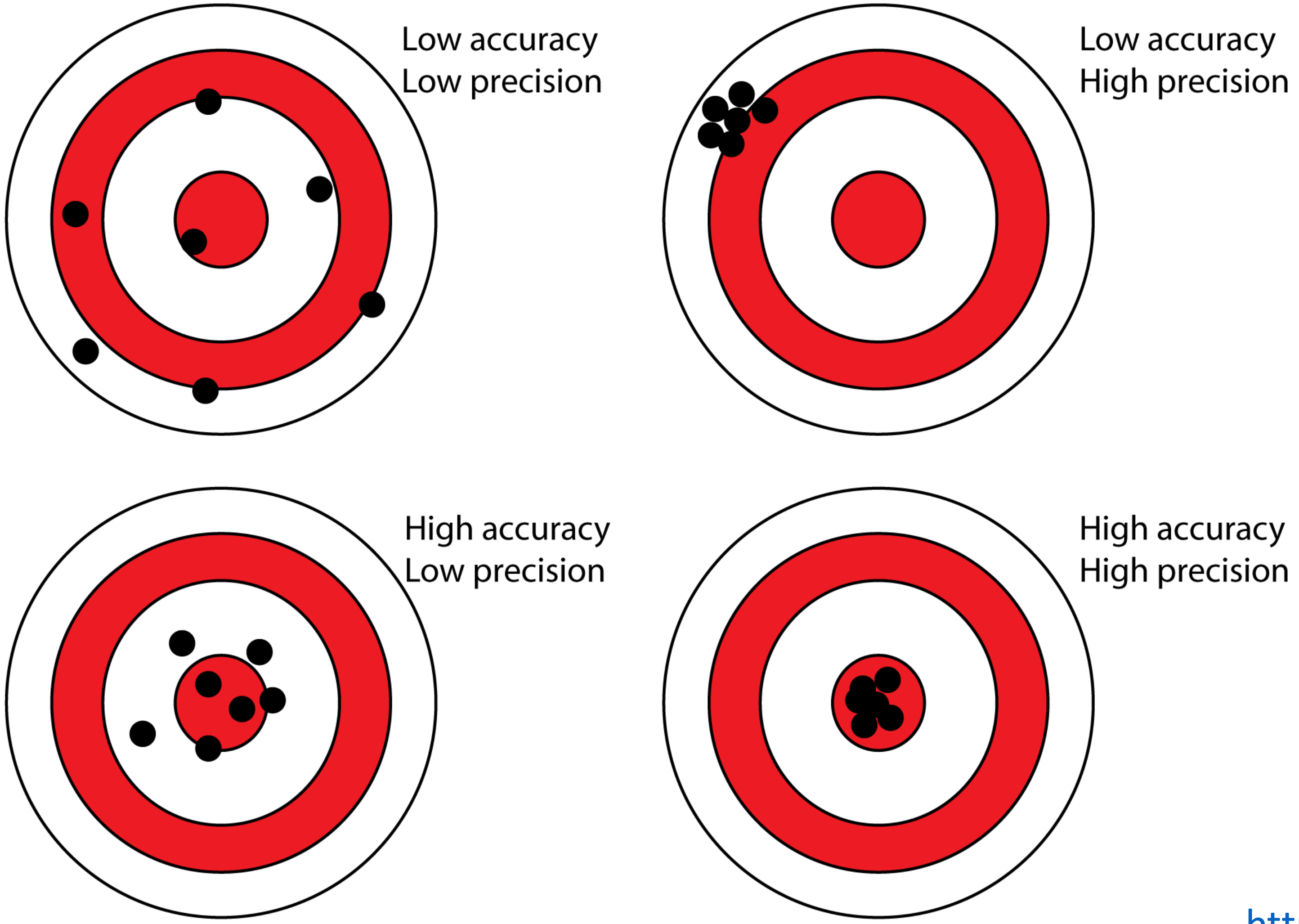


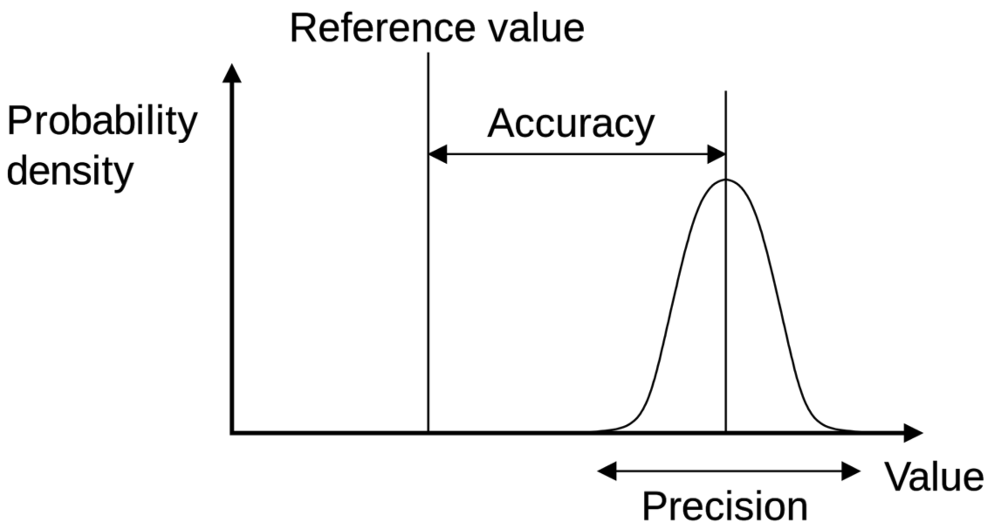
Simulations

- Analytical approach (determinist)
- Monte-Carlo approach (stochastic)
- Hybrid approach

- Validation : compare to measurements
- Calibration: commissioning, parameters
- Parameters: tradeoff precision-speed
- Uncertainties: precision, accuracy

Precision/accuracy - précision/exactitude

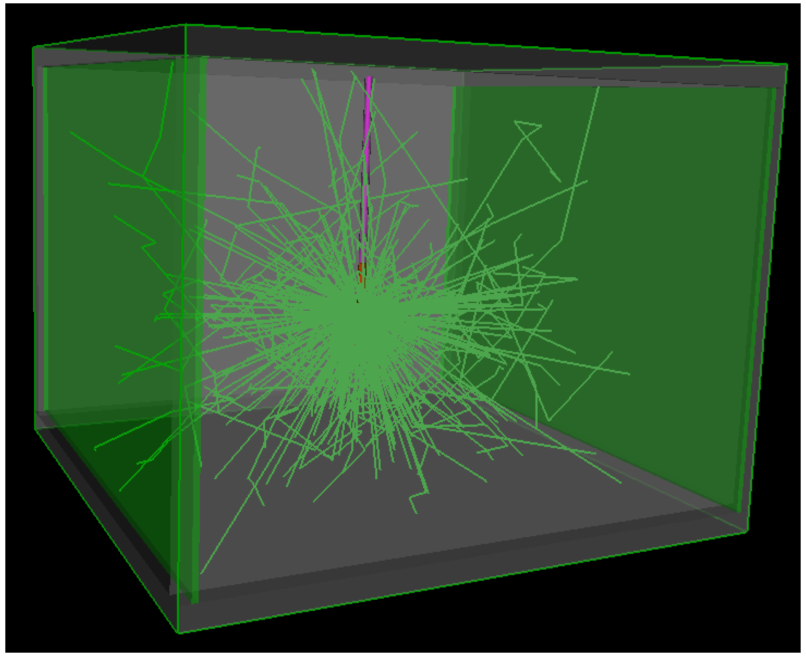




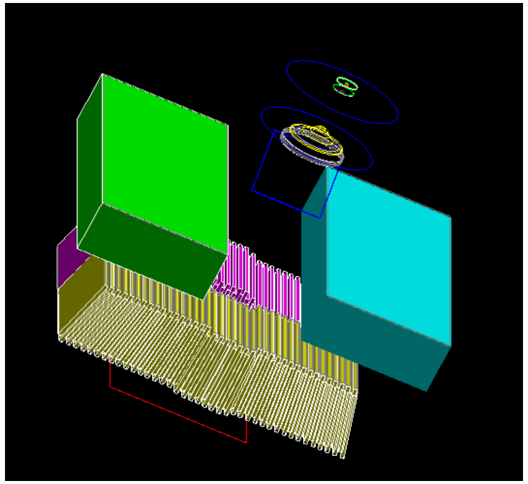
https://en.wikipedia.org/wiki/Accuracy_and_precision

Monte-Carlo in Medical Physics

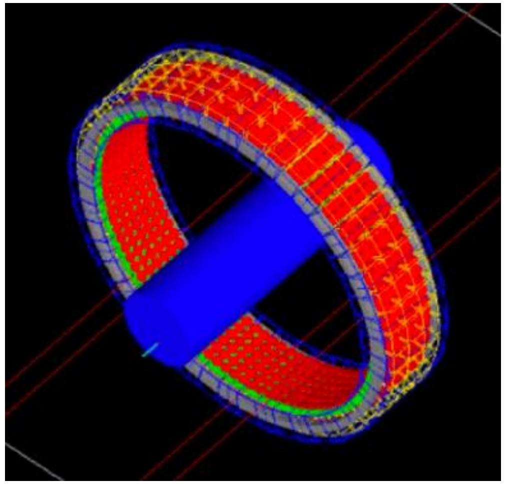
- Simulate particles path, interactions, energy loss
- Monte-Carlo considered as a reference method



Particles tracking



Radiation Therapy



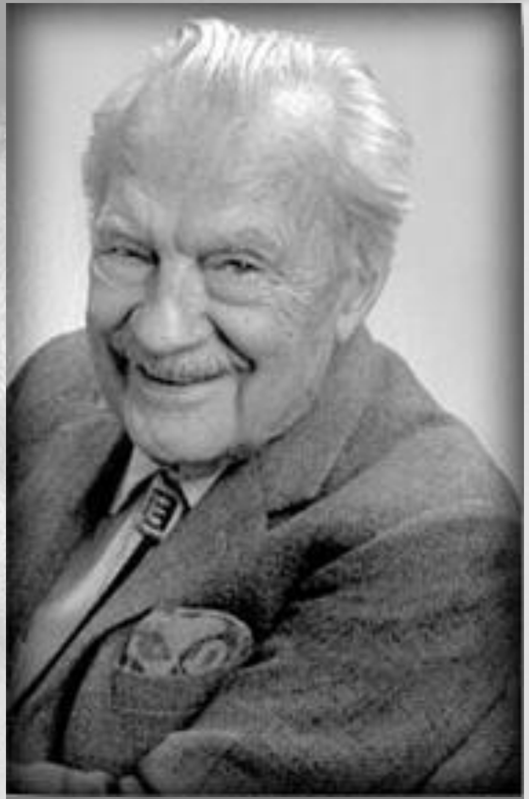
Nuclear Medicine

Robert Oppenheimer

Nuclear physics **Monte Carlo** simulations

Edward Teller

Stanisław Ulam



Nicholas Metropolis

ENIAC 1947

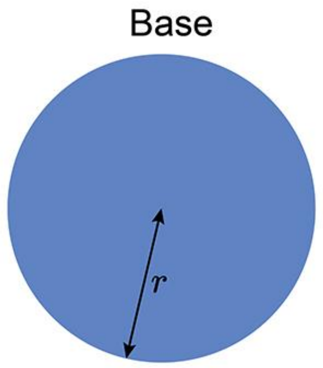
Metropolis, Nicholas; Stanislaw Ulam (**1949**).
"The Monte Carlo method". Journal of the American Statistical Association. 44 (247): 335-341
doi:10.1080/01621459.1949.10483310

Monte-Carlo

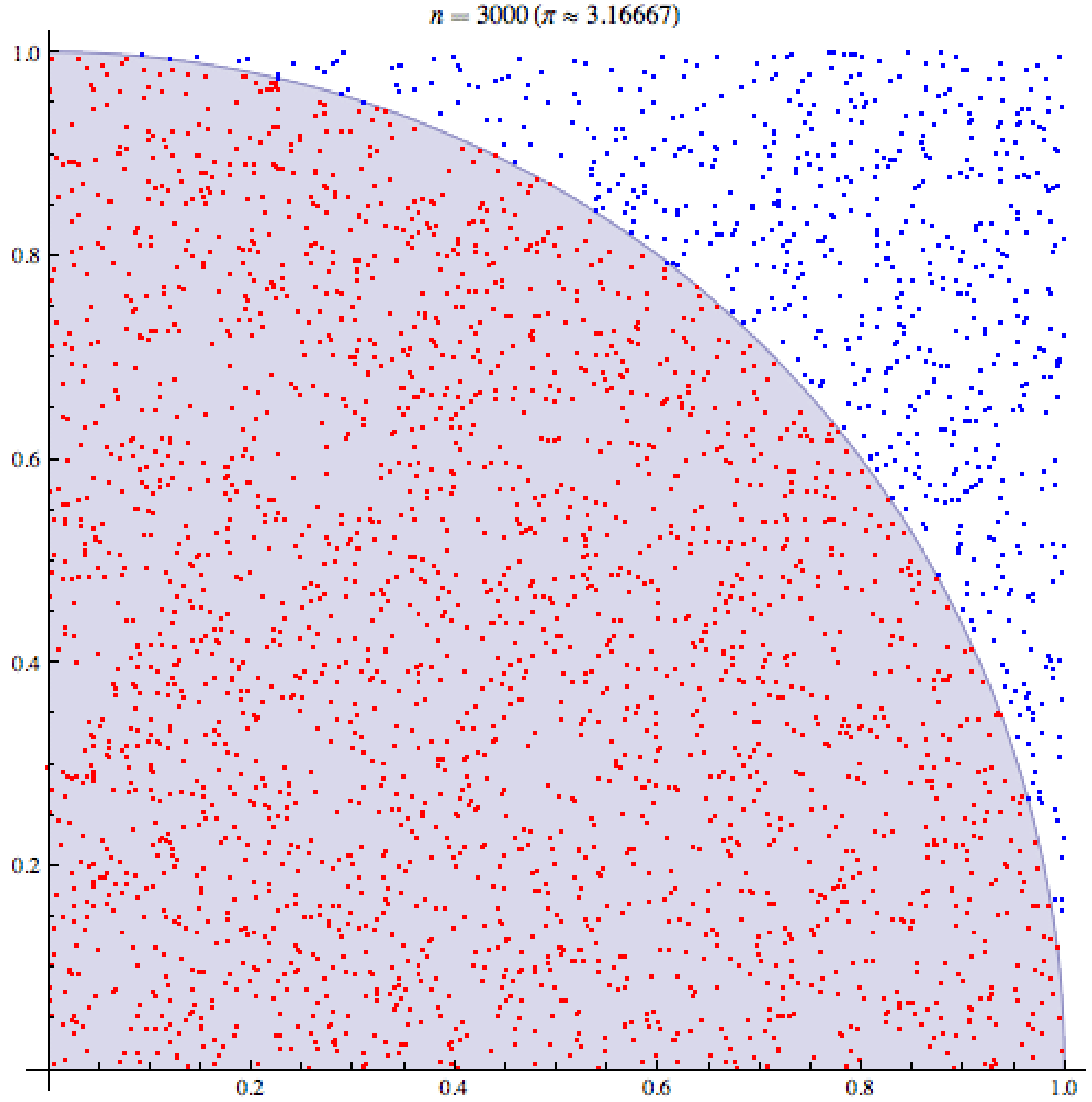
- History : WW2, Manhattan Project, casinos
- What ?
  A class of computational algorithms that rely on repeated stochastic sampling to compute results.
- Why ?
  When the problem is *many-dimensional* and approximations that factor the problem into products of lower dimensional problems are inaccurate.
  A less important reason is that if one has a *complicated geometry*, a MC algorithm may be simpler than other choices.
- Drawback ?
  There is a statistical error. Sometimes there is a tradeoff between statistical error and systematic error and one needs to find the best compromise. Could be slow to converge.

[Cyrus J. Umrigar]

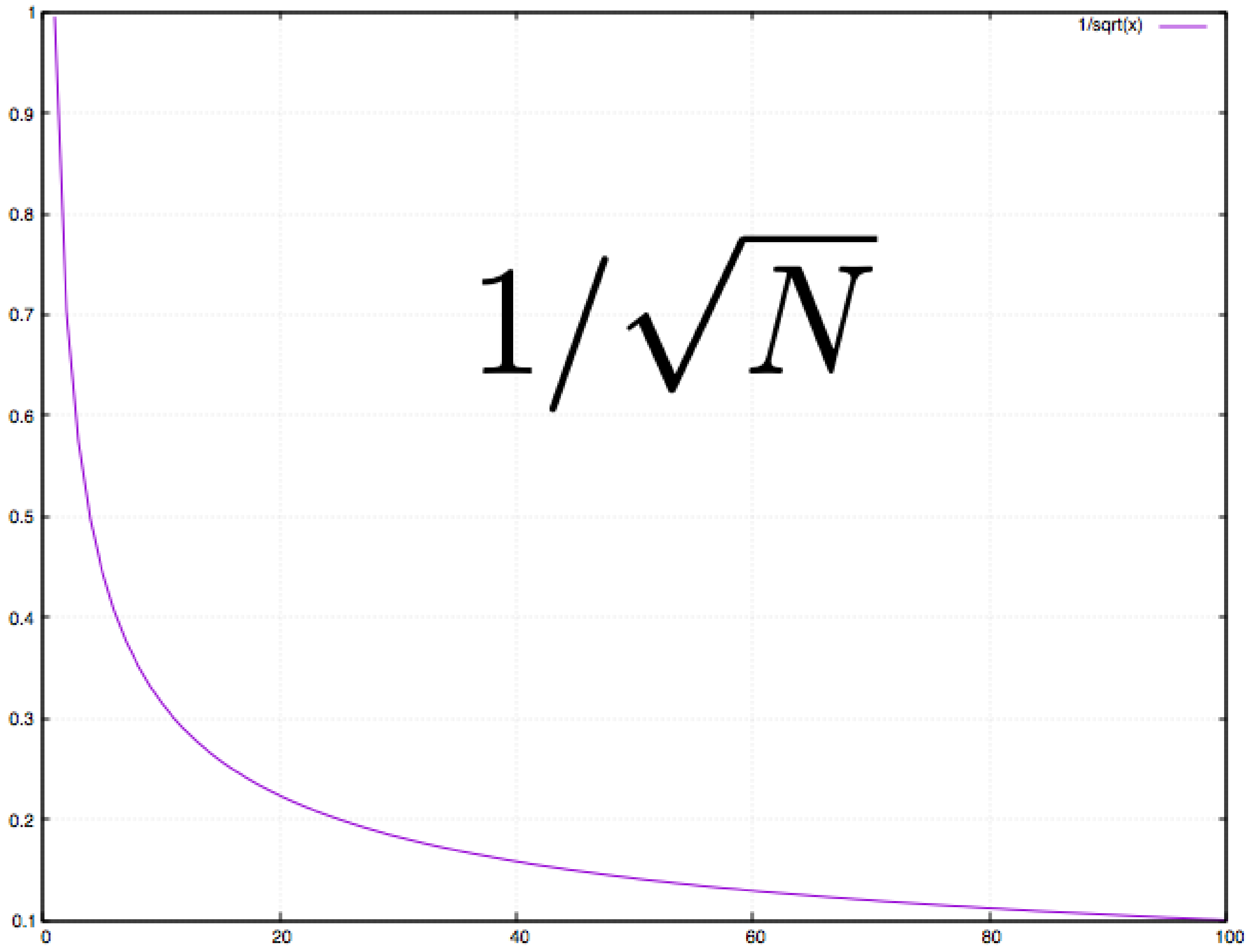
Monte-Carlo estimation



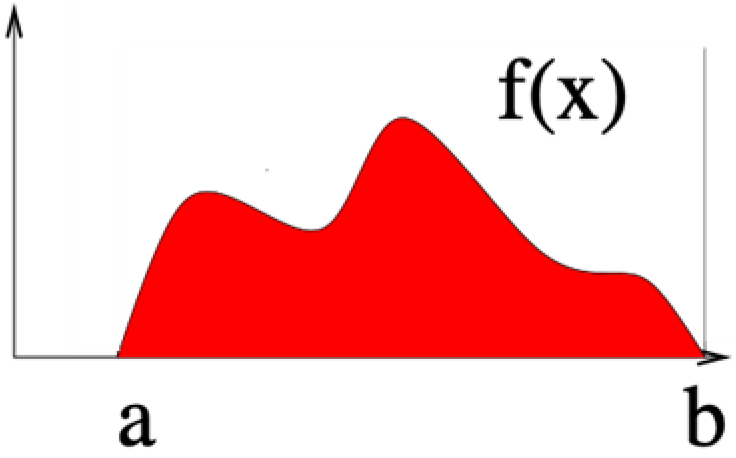
Area = πr^2



… chaque chiffre significatif supplémentaire,
nécessite un coût de simulation 100 fois supérieur.

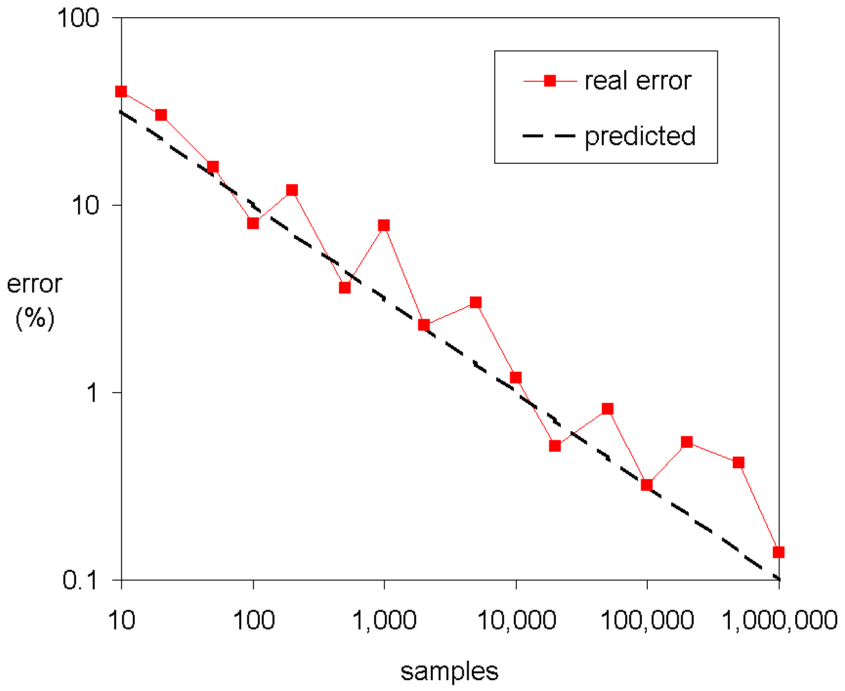


Monte-Carlo



$$I = \int_a^b dx\, f(x)$$

$$I \approx \frac{b-a}{N} \sum_{i=1}^{N} f(x_i)$$



Error: $\propto 1/\sqrt{N}$

Error: central limit theorem
independent of the dimension

Monte-Carlo simulations

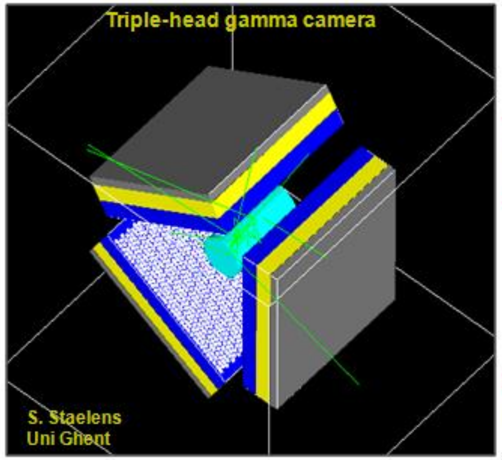
- Requirement : system and physical processes can be modelled from known probability density functions (pdfs)
- Random sampling of the pdfs

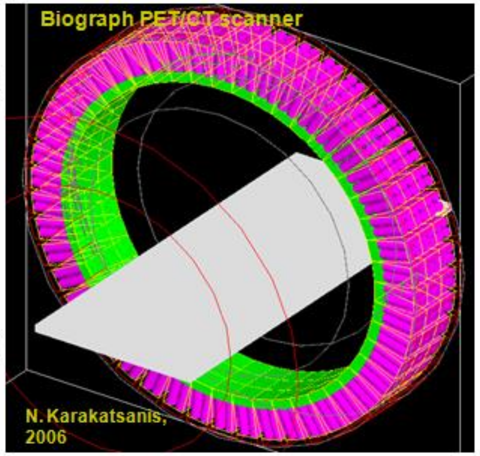
- Notions :
  - Random number generator (seed, period)
  - Sampling techniques ; cumulated pdf ; importance sampling
  - Statistical uncertainties / errors ; stopping criteria
  - Variance reduction technique
  - Convergence rate (speed, efficiency)

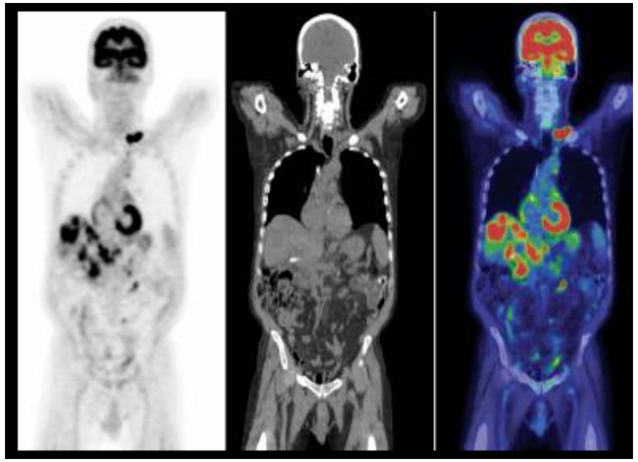
Applications

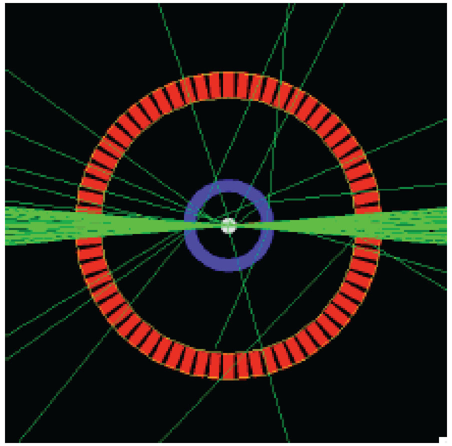
Nuclear and radiation imaging modalities

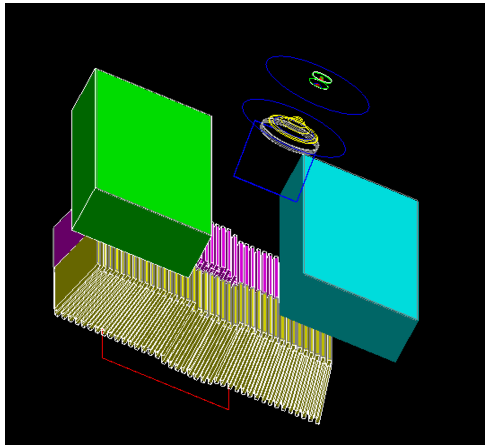
- PET
- SPECT
- Compton Camera
- Prompt gamma
- Proton Rad/CT
- CT
  - Cone Beam
  - Spectral CT
  - Dual Energy
  - Phase Contrast









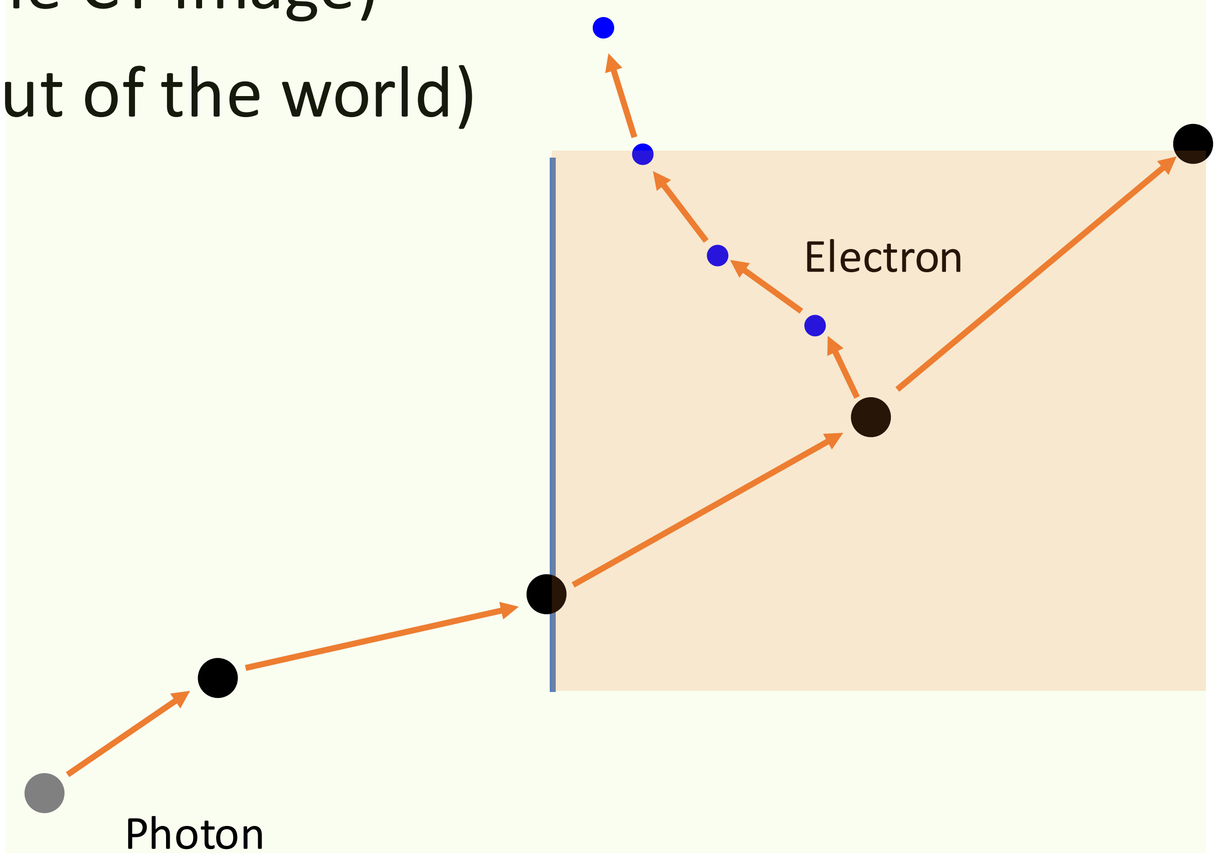


Particles tracking

Particles tracking

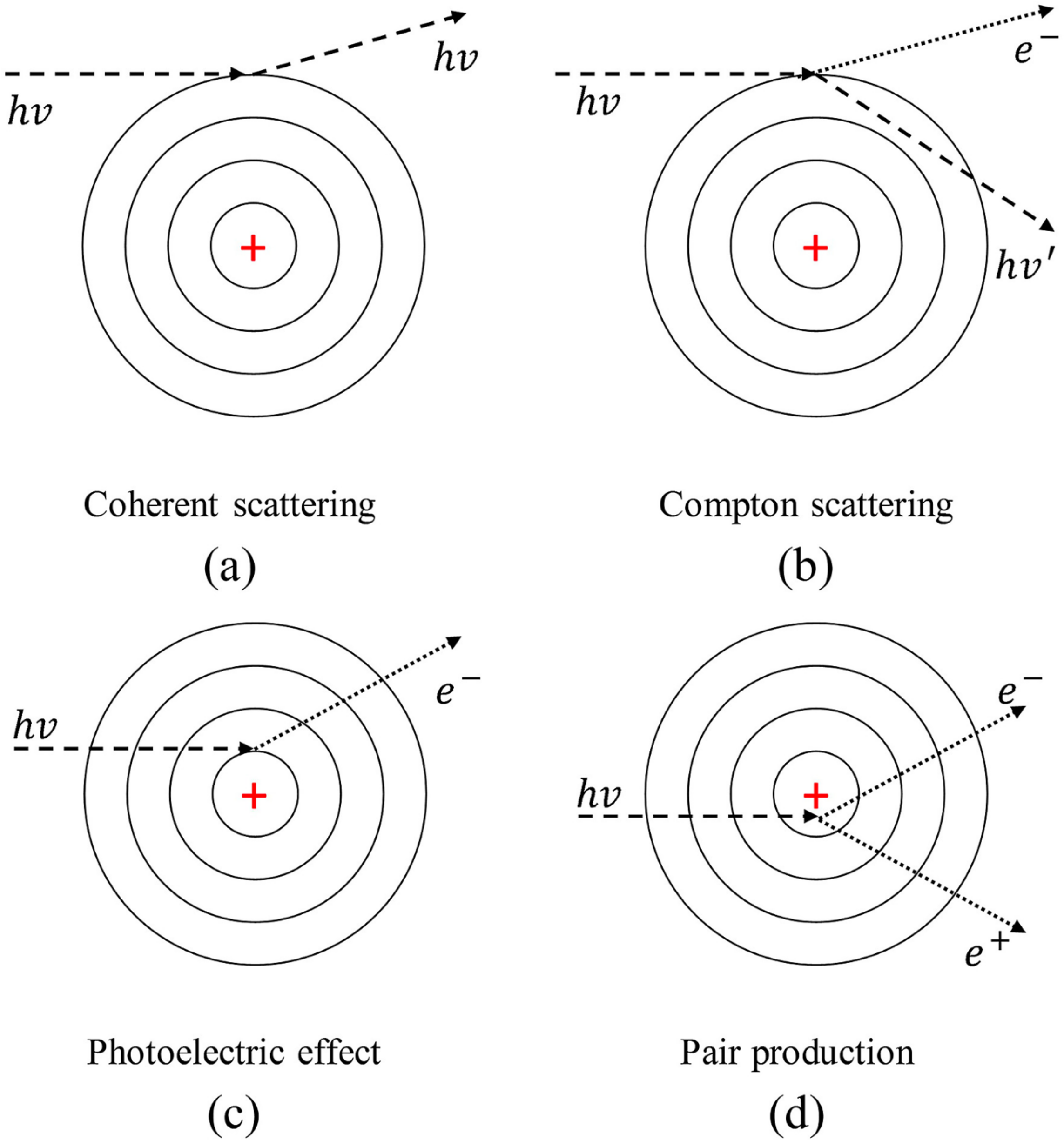
- From the « *source* » (*ex nihilo* particle creation)
- Through the « *phantom* » (or the CT image)
- To the « *detector* » (or out of the world)

- Track all particles individually
  - Tracking path, decomposed in steps
  - Several physical processes
  - Probability distributions



Physical processes

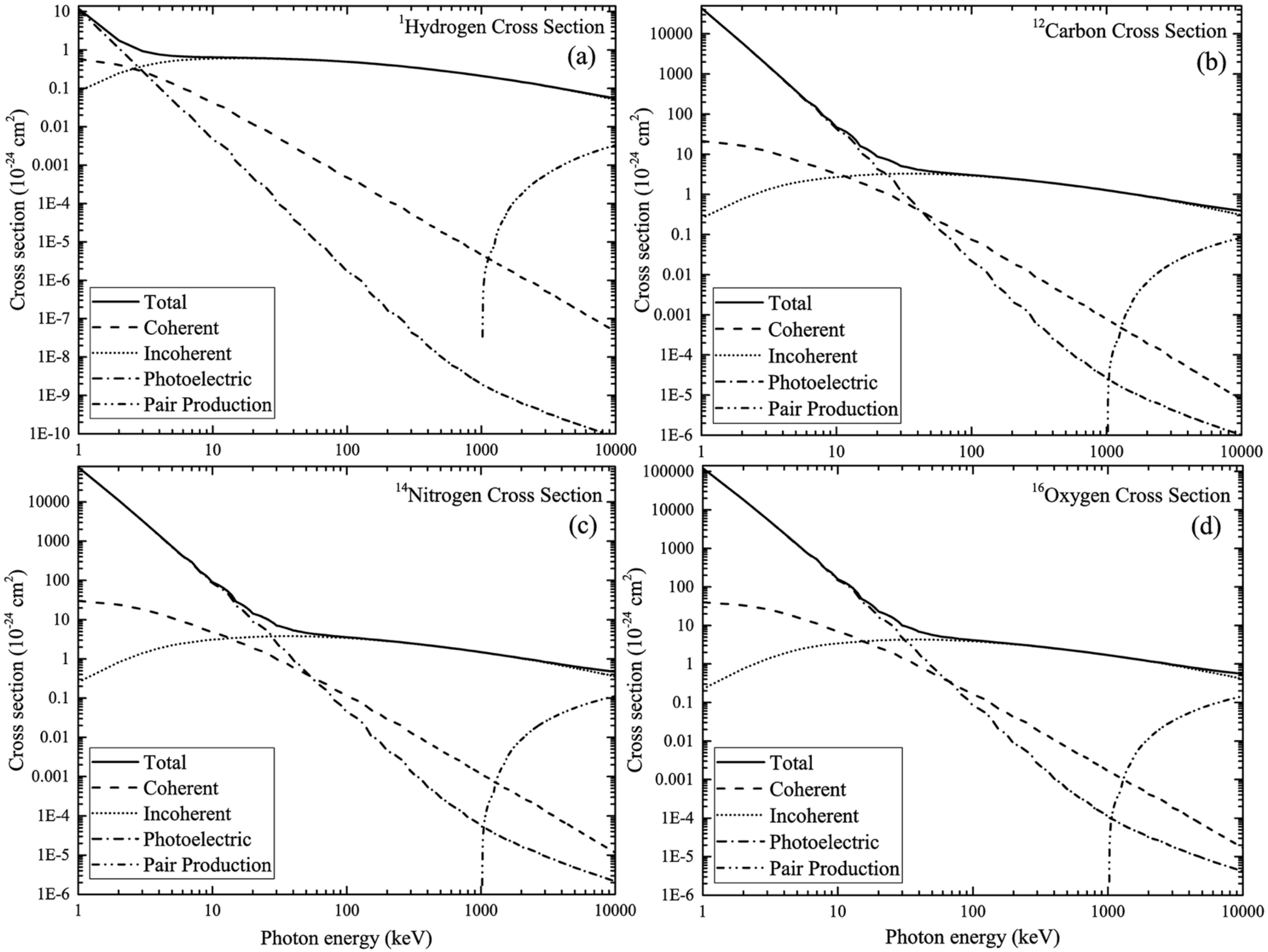
- Example for photon
  - Scattering (Rayleigh, Compton)
  - Photoelectric
  - Pair production
  - Photonuclear …



Physical processes

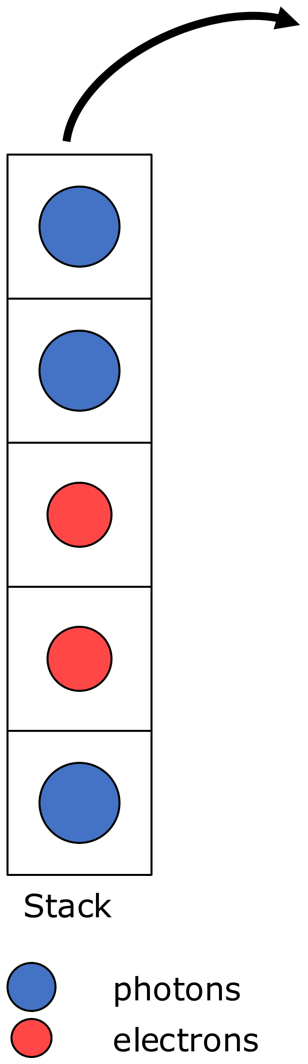
- Cross section
  - Interaction probability
  - wrt material
  - wrt energy
- For all particles
- For all processes

- Large database needed



MC engine - Tracking loop (simplified)

Start with particles from source

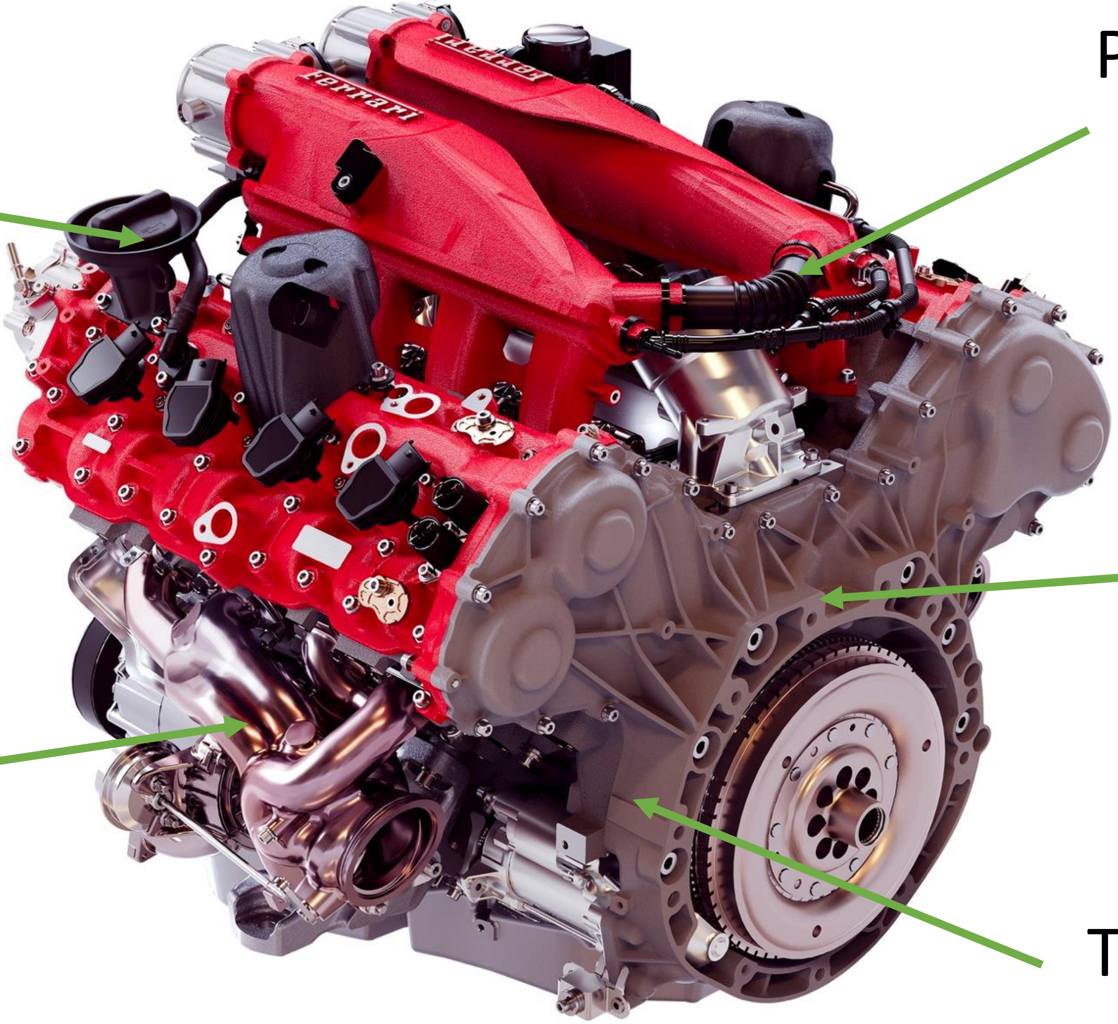


- Un-stack a particle p
  - Consider properties of p (E, position, direction, time …)
  - Consider current material composition at position
  - **Sample** random distance to next interactions
    - Given a set of possible physical processes
    - Given the properties & material
  - **Transport** p to this interaction point
    - Check not exiting the current material
    - Check not exiting the “world”
  - **Model** the selected interaction
    - If absorption: end
    - If new particle: insert in the stack
    - Change properties, generate secondary particles (stack)
  - Next step
- Next particle

Monte Carlo engine

Particle management

Physical processes database



Pseudo-Random number generator

Geometrical elements in the simulation scene

Tracking loop

Difficulty & Challenges

- Computation time: Variance Reduction Technique
- Tradeoff: speed – complexity – accuracy

- Validation against experiments (uncertainties)
- Access to industrial data
- Input models (physics, biological …)
- Multi-scale aspects
- Multi-disciplinary: physics, mathematic, biology, medicine, computer sciences

Monte Carlo simulations evolution

- Around 60+ years evolution
  - More accurate physical databases
  - More generic codes (MCNPX, EGSNRC, Penelope, Geant4, Gate)
  - Faster algorithms
  - Use of powerful computing infrastructures (cluster, GPU)

- However
  - Increasing need for detailed and accurate physical processing (TOF, SiPM, CZT, etc)
  - Still long simulations times
  - Generic vs Specific codes
  - IA ?

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Phys. Med. Biol. **51** (2006) R287–R301 doi:10.1088/0031-9155/51/13/R17

REVIEW

Fifty years of Monte Carlo simulations for medical physics*

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Received 23 February 2006, in final form 3 May 2006
Published 20 June 2006
Online at stacks.iop.org/PMB/51/R287

Abstract

Monte Carlo techniques have become ubiquitous in medical physics over the last 50 years with a doubling of papers on the subject every 5 years between the first PMB paper in 1967 and 2000 when the numbers levelled off. While recognizing the many other roles that Monte Carlo techniques have played in medical physics, this review emphasizes techniques for electron–photon transport simulations. The broad range of codes available is mentioned but

Available MC codes

- **Industrial software** : in TPS
- **Multi-purpose, research** : MCNPX, EGS-nrc, Penelope, Geant4, GATE, Fluka, …

- **Characteristics ?**
  - Available physics : particles, models, energy limits, models, database tables
  - Description of various geometrical shapes (voxels etc)
  - Description of various source types
  - Available types of observable (dose)
  - Variance reduction techniques
  - Possibility to evolve
  - Validation – reputation
  - Ease of use
  - Community, documentation
  - Code language,
  - Open-source

1 Go to wooclap.com

2 Enter the event code in the top banner

Event code
JOPIXG

1 Send @JOPIXG to 06 44 60 96 62

2 You can participate

Disable answers by SMS

Geant4 & GATE

Geant4

A SIMULATION TOOLKIT

- Geant4 is a **toolkit**
- Developed by CERN & international community
- Since 1999 ; about 2 releases/year ; now version 11.3 (December 2023)
- Features :

  "Geant4 is a toolkit for simulating the passage of particles through matter. It includes a complete range of functionality including tracking, geometry, physics models and hits. "

- LHC : Higgs boson, high energy physics
- Large user community
- Open-source

- **Usage**
  - Code your simulation in C++
  - Use classes, functions provided by Geant4
  - Compile your code, obtain a executable
  - Run it

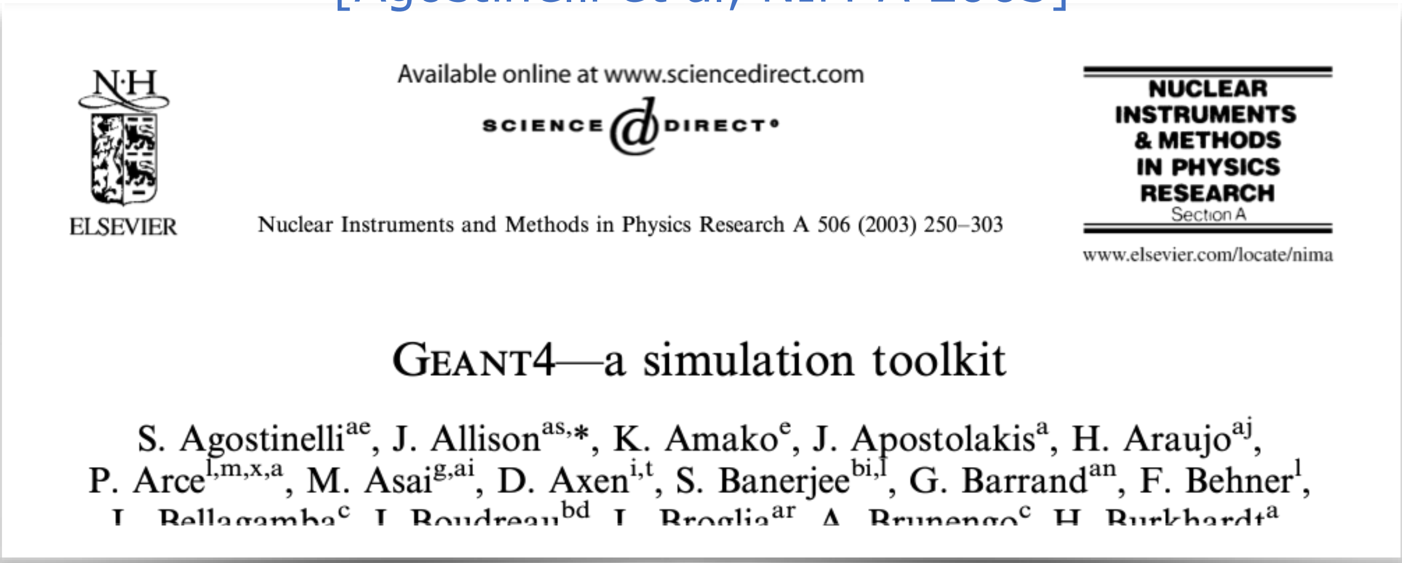
open source ™

Geant4

- Web site
  - Download code
  - Installation guide
  - User guide
  - Developer guide
  - Mailing list

- Workshop, formation

[Agostinelli et al, NIM-A 2003]



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Nuclear Instruments and Methods in Physics Research A 506 (2003) 250–303

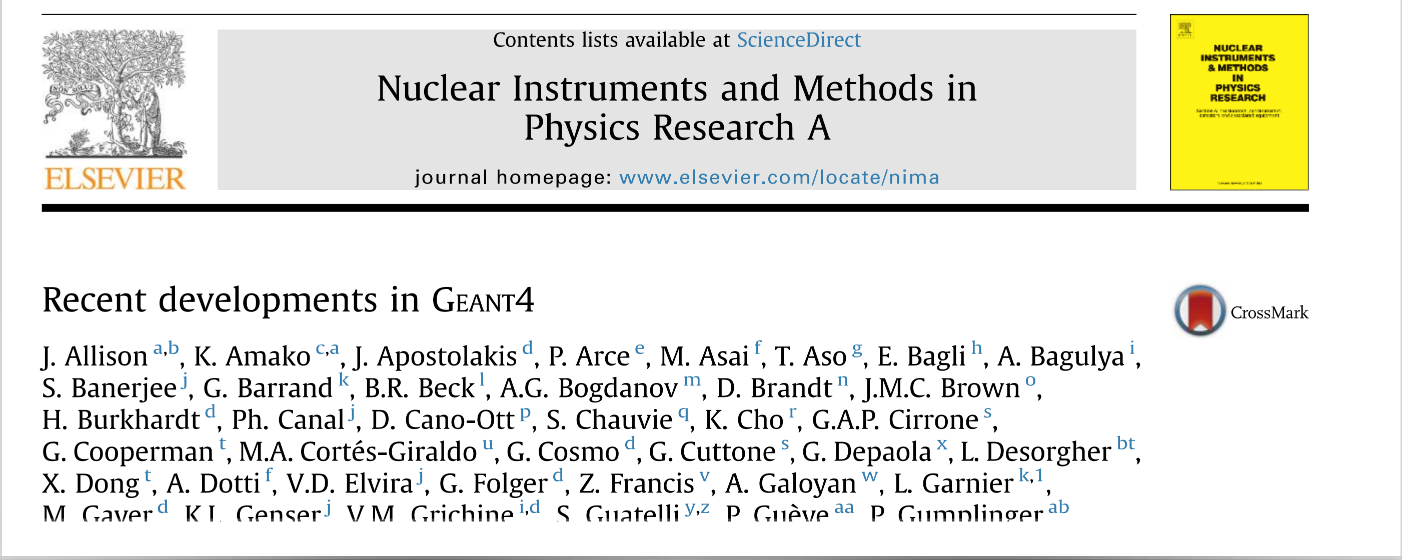
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

www.elsevier.com/locate/nima

GEANT4—a simulation toolkit

S. Agostinelli[ae], J. Allison[as,*], K. Amako[e], J. Apostolakis[a], H. Araujo[aj], P. Arce[l,m,x,a], M. Asai[g,ai], D. Axen[i,t], S. Banerjee[bi,l], G. Barrand[an], F. Behner[l],

[Alisson et al, NIM-A 2016]



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Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

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Recent developments in GEANT4

CrossMark

J. Allison[a,b], K. Amako[c,a], J. Apostolakis[d], P. Arce[e], M. Asai[f], T. Aso[g], E. Bagli[h], A. Bagulya[i], S. Banerjee[j], G. Barrand[k], B.R. Beck[l], A.G. Bogdanov[m], D. Brandt[n], J.M.C. Brown[o], H. Burkhardt[d], Ph. Canal[j], D. Cano-Ott[p], S. Chauvie[q], K. Cho[r], G.A.P. Cirrone[s], G. Cooperman[t], M.A. Cortés-Giraldo[u], G. Cosmo[d], G. Cuttone[s], G. Depaola[x], L. Desorgher[bt], X. Dong[t], A. Dotti[f], V.D. Elvira[j], G. Folger[d], Z. Francis[v], A. Galoyan[w], L. Garnier[k,1],

Create a simulation with G4

- Geant4 simulation
- Need C++ code
  - Main.cpp
  - +3 files (classes)
  - Compile to get executable file

- Powerful, but can be tedious
- Not easy to re-use among users

Listing 1 Simplest example of main()¶

```
#include "G4RunManager.hh"
#include "G4UImanager.hh"

#include "ExG4DetectorConstruction01.hh"
#include "ExG4PhysicsList00.hh"
#include "ExG4ActionInitialization01.hh"

int main()
{
  // construct the default run manager
  G4RunManager* runManager = new G4RunManager;

  // set mandatory initialization classes
  runManager->SetUserInitialization(new ExG4DetectorConstruction01);
  runManager->SetUserInitialization(new ExG4PhysicsList00);
  runManager->SetUserInitialization(new ExG4ActionInitialization01);

  // initialize G4 kernel
  runManager->Initialize();

  // get the pointer to the UI manager and set verbosities
  G4UImanager* UI = G4UImanager::GetUIpointer();
  UI->ApplyCommand("/run/verbose 1");
  UI->ApplyCommand("/event/verbose 1");
  UI->ApplyCommand("/tracking/verbose 1");

  // start a run
  int numberOfEvent = 3;
  runManager->BeamOn(numberOfEvent);

  // job termination
  delete runManager;
  return 0;
}
```

GATE

Geant4 Application for Emission Tomography, Transmission Tomography, Radiotherapy

- **GATE is a Geant4 application**
  - Written in C++
  - Using the Geant4 toolkit
  - Provide extension to the Geant4 macro language

- **Applications**
  - PET, SPECT, CT imaging
  - Dosimetry radiation therapy, hadrontherapy, molecular radiotherapy, brachytherapy,
  - Detector design, optimisation of acquisition protocol, assessment of quantification methods, etc …

GATE: a brief history

- Initial idea around 2001 (C. Morel, I. Buvat et al)
- First release in 2004 (S. Jan): TEP, SPECT
- Increase range of application since Gate 6 (2010): radiation therapy, particle therapy
- About 1-2 releases/year
- Now: **GATE 10**

More than 100 peer-reviewed GATE-related papers produced by members of the collaboration

- Best paper citation price in PMB 2004
- Best paper citation price in PMB 2011

GATE: reference papers

Phys Med Biol 2004
Phys Med Biol 2011
Medical physics 2014
Phys Med Biol 2021
Phys Med Biol 2022

INSTITUTE OF PHYSICS PUBLISHING PHYSICS IN MEDICINE AND BIOLOGY
Phys. Med. Biol. **49** (2004) 4543–4561 PII: S0031-9155(04)80763-2

GATE: a simulation toolkit for PET and SPECT

S Jan[1], G Santin[2,24], D Strul[2,25], S Staelens[3], K Assié[4], D Autret[5], S Avner[6], R Barbier[7], M Bardiès[5], P M Bloomfield[8], D Brasse[6], V Breton[9], P Bruyndonckx[10], I Buvat[4], A F Chatziioannou[11], Y Choi[12], Y H Chung[12], C Comtat[1], D Donnarieix[9,13], L Ferrer[5], S J Glick[14], C J Groiselle[14], D Guez[15], P-F Honore[15], S Kerhoas-Cavata[15], A S Kirov[16], V Kohli[11], M Koole[3], M Krieguer[10], D J van der Laan[17], F Lamare[18], G Largeron[7], C Lartizien[19], D Lazaro[9], M C Maas[17], L Maigne[9], F Mayet[20], F Melot[20], C Merheb[15], E Pennacchio[7], J Perez[21], U Pietrzyk[21], F R Rannou[11,22], M Rey[2], D R Schaart[17], C R Schmidtlein[16], L Simon[2,26], T Y Song[12], J-M Vieira[2], D Visvikis[18], R Van de Walle[3], E Wieërs[10,23] and C Morel[2]

A review of the use and potential of the GATE Monte Carlo simulation code for radiation therapy and dosimetry applications

David Sarrut[a)]
Université de Lyon, CREATIS; CNRS UMR5220; Inserm U1044; INSA-Lyon; Université Lyon 1; Centre Léon Bérard, France

Manuel Bardiès
Inserm, UMR1037 CRCT, F-31000 Toulouse, France and Université Toulouse III-Paul Sabatier, UMR1037 CRCT, F-31000 Toulouse, France

Nicolas Boussion
INSERM, UMR 1101, LaTIM, CHU Morvan, 29609 Brest, France

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Phys. Med. Biol. **56** (2011) 881–901 doi:10.1088/0031-9155/56/4/001

GATE V6: a major enhancement of the GATE simulation platform enabling modelling of CT and radiotherapy

S Jan[1], D Benoit[2], E Becheva[1], T Carlier[3,4], F Cassol[5], P Descourt[6], T Frisson[7], L Grevillot[7], L Guigues[7], L Maigne[8], C Morel[5], Y Perrot[8], N Rehfeld[2], D Sarrut[7], D R Schaart[9], S Stute[2], U Pietrzyk[10], D Visvikis[6], N Zahra[7] and I Buvat[2]

IOP Publishing *Phys. Med. Biol.* **66** (2021) 10TR03 https://doi.org/10.1088/1361-6560/abf276

Physics in Medicine & Biology IPEM Institute of Physics and Engineering in Medicine

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TOPICAL REVIEW

Advanced Monte Carlo simulations of emission tomography imaging systems with GATE

David Sarrut[1,*], Mateusz Bała[2], Manuel Bardiès[3], Julien Bert[4], Maxime Chauvin[5], Konstantinos Chatzipapas[6], Mathieu Dupont[7], Ane Etxebeste[1], Louise M Fanchon[8], Sébastien Jan[9], Gunjan Kayal[5,10], Assen S Kirov[8], Paweł Kowalski[11], Wojciech Krzemien[11], Joey Labour[1], Mirjam Lenz[12,13], George Loudos[6], Brahim Mehadji[7], Laurent Ménard[14,15], Christian Morel[7], Panagiotis Papadimitroulas[6], Magdalena Rafecas[16], Julien Salvadori[17], Daniel Seiter[18], Mariele Stockhoff[19], Etienne Testa[20], Carlotta Trigila[21], Uwe Pietrzyk[13], Stefaan Vandenberghe[19], Marc-Antoine Verdier[14,15], Dimitris Visvikis[4], Karl Ziemons[12], Milan Zvolský[16] and Emilie Roncali[21]

1 Université de Lyon, CREATIS, CNRS UMR5220, Inserm U1294, INSA-Lyon, Université Lyon 1, Lyon, France
2 Jagiellonian University, Kraków, Poland
3 Cancer Research Institute of Montpellier, U1194 INSERM/ICM/Montpellier University, 208 Av des Apothicaires, F-34298 Montpellier

GATE: a collaboration

- OpenGate Collaboration
  - About 22 labs, worldwide (40% in France)
  - Spoken person : Lydia Maigne
  - Technical coordinator : David Sarrut
- Organize the development of GATE
  - Meetings, projects, teaching etc
  - Developers : open-source
  - Funding
- **GATE is a collaboration before being a software**

http://www.opengatecollaboration.org

gate-users@lists.opengatecollaboration.org

https://opengate.readthedocs.io

GATE: limitations

- Too few numbers of developers
- Documentation to be improved
- Macro vs C++
- Visualisation not perfect (Geant4)
- Support

GATE: limitations

- Too few numbers of developers
- Documentation to be improved
- ~~Macro vs C++~~ **Python vs C++**
- Visualisation not perfect (Geant4)
- Support

Use of Gate

Gate : **imaging** and **dosimetry** in medical physics

Published studies:

- TEP, SPECT
- RT photon, low and high energy
- X-ray imaging
- RT hadron proton, carbon, helium
- RT internal dosimetry (all isotopes)
- Hadron-PET, prompt-gamma, vertex imaging