Monte Carlo Radiation Transport:

Current Capabilities and Future Directions

Zdenka Kuncic

Institute of Medical Physics,
School of Physics, University of Sydney

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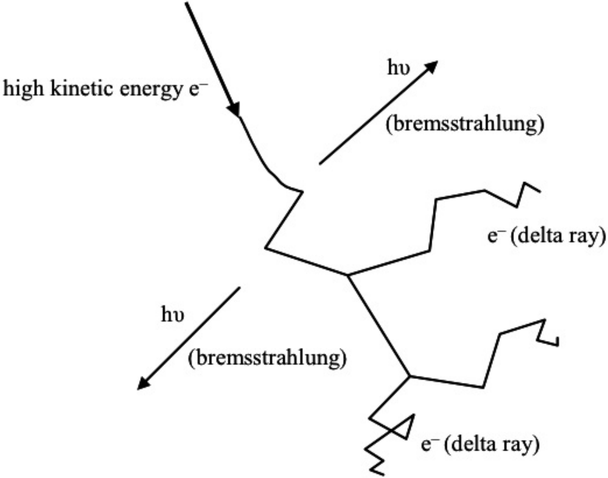
Radiation Transport

- MC is most successful method for simulating stochastic processes in nature – e.g. particle transport through media
- originally developed to model neutron and photon diffusion in nuclear reactors
  - Spencer & Wolff 1953, *Penetration and diffusion of hard X-rays: Polarization effects*, Phys. Rev. 90, 510–14
- subsequently further developed to model charged particle transport (e.g. electrons, protons)
- earliest medical physics applications in nuclear medicine:
  - Berger 1968, *MIRD Pamphlet 2: Energy deposition in water by photons from point isotropic sources*, J. Nuc. Med. 9, 15–25



Life history of a fast electron

The Boltzmann Transport Equation

- physics of radiation transport governed by Boltzmann transport equation
- involves integration of particle interaction probabilities over x, y, z, t and over all directions $\Omega_1, \Omega_2, \Omega_3 \Longrightarrow$ multidimensional integration

$$\left[\frac{\partial}{\partial s} + \boldsymbol{\Omega}\cdot\boldsymbol{\nabla} + \Sigma(E)\right]\Phi(\mathbf{x}, \boldsymbol{\Omega}, s) = \int \Sigma(\boldsymbol{\Omega}\cdot\boldsymbol{\Omega}', E)\Phi(\mathbf{x}, \boldsymbol{\Omega}', s)\, d\Omega'$$

Φ = particle flux density

E = particle energy

$\boldsymbol{\Omega}$ = initial particle propagation direction (flight path)

$\boldsymbol{\Omega}'$ = propagation direction after interaction

$\Sigma(E)$ = total cross-section per unit path length
$\Sigma(\mathbf{\Omega} \cdot \mathbf{\Omega}', E)$ = differential cross-section per unit length

These are related by:

$$\Sigma(E) = \int \Sigma(\mathbf{\Omega}{\cdot}\mathbf{\Omega}', E)\, d\Omega' = \int_0^{2\pi} \int_0^{\pi} \Sigma(\mathbf{\Omega}{\cdot}\mathbf{\Omega}', E)\ \sin\theta' d\theta'\, d\phi'$$

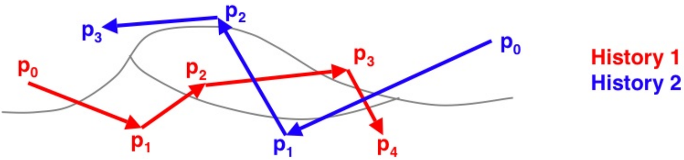
- PDF for particle *interactions* is

$$P(\mathbf{\Omega}) = \frac{1}{\Sigma}\frac{d\Sigma}{d\Omega'} = \frac{1}{\sigma}\frac{d\sigma}{d\Omega'}$$

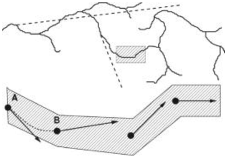
- PDF for particle *transport* is also needed - e.g. for photons, step-size is obtained by sampling the exponential PDF: $s = -\lambda \ln(1-\zeta)$

Particle Histories

- MC randomly selects a set of histories $\mathbf{p}_j = (\mathbf{x}_j, \mathbf{\Omega}_j, s_j, E_j)$ from all possible trajectories $\Phi(\mathbf{x}, \mathbf{\Omega}, s, E)$
- a statistical estimate of quantities of interest are obtained from the expectation value $\langle Q \rangle$, averaged over all simulated histories

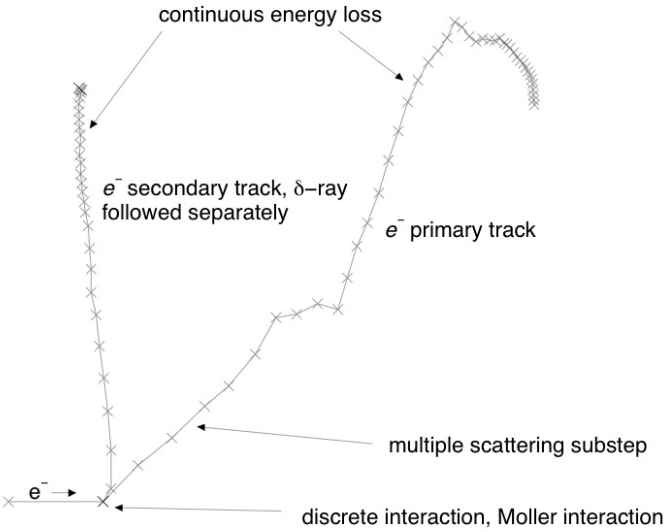


- dose computed *stochastically* from first principles



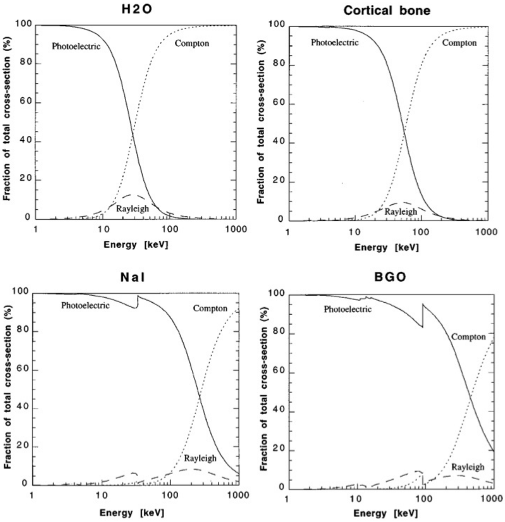
condensed history

Example: Electron tracks



3 components of a complete MC radiation transport code:

1. interaction cross-section physics data



2. algorithms for particle transport
3. geometry specifications

Current Capabilities

Two most widely used, supported, open-source MC codes for medical physics applications are:

1. EGSnrc – Electron Gamma Shower, developed by National Research Council, Canada:

   `www.irs.inms.nrc.ca/EGSnrc/EGSnrc.html`

2. Geant4 – software toolkit developed by multinational collaboration (CERN, ESA, Fermilab, SLAC, KEK, UK/STFC...)

   `geant4.web.cern.ch/geant4/`

Also: MCNP (LANL), Penelope (low-energy physics),...

In nuclear medicine:

- **SimSET** – Simulation System for Emission Tomography (SPECT & PET imaging)
- **SimSPECT** – includes electron transport also
- **MABOSE** – internal radionuclide dosimetry (based on MIRD schema)
- **GATE** – G4 Application for Emission Tomography

Applications:

- diagnostic & therapeutic nuclear medicine imaging
- nuclear medicine dosimetry (absorbed fractions, dose-point kernels, pharmacokinetic modelling, patient-specific)
- radiation protection in nuclear medicine (shielding, detectors & monitoring equipment)

see Zaidi 1999, *Relevance of accurate Monte Carlo modeling in nuclear medical imaging*, Med. Phys. 26, 574

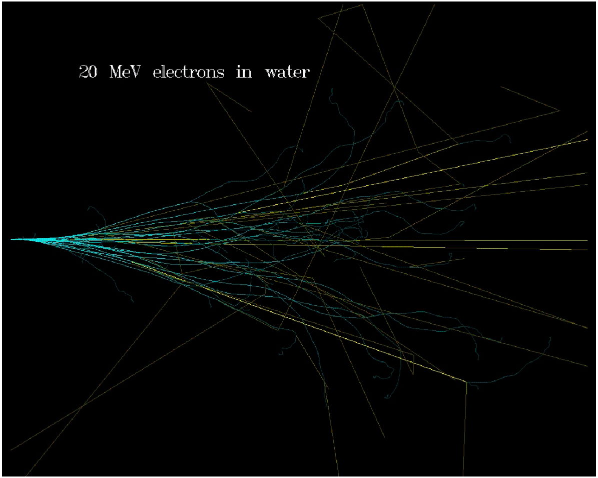
EGSnrc

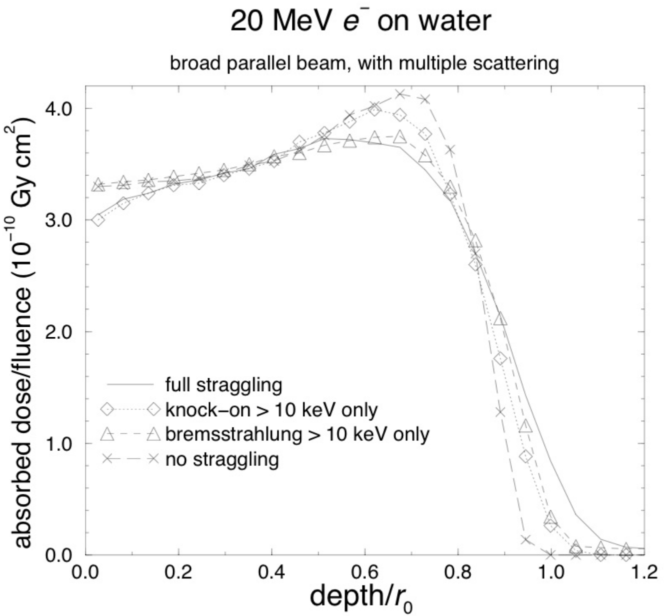
Pros:

- easy to use
- written in Fortran

Cons:

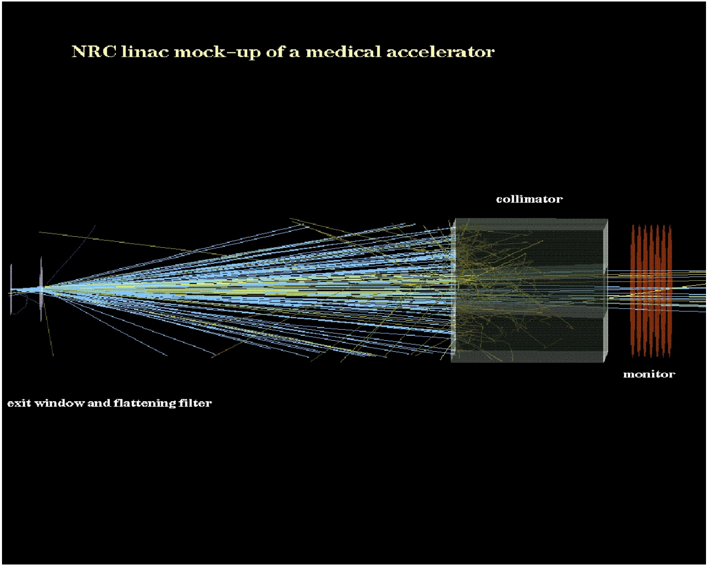
- medical physics applications only




20 MeV e⁻ on water
broad parallel beam, with multiple scattering
absorbed dose/fluence (10⁻¹⁰ Gy cm²)
depth/r0
full straggling
knock–on > 10 keV only
bremsstrahlung > 10 keV only
no straggling
0.0
1.0
2.0
3.0
4.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2

EGSnrc/BEAMnrc

Rogers DWO +, Med. Phys. 22(5), 503, 1995.



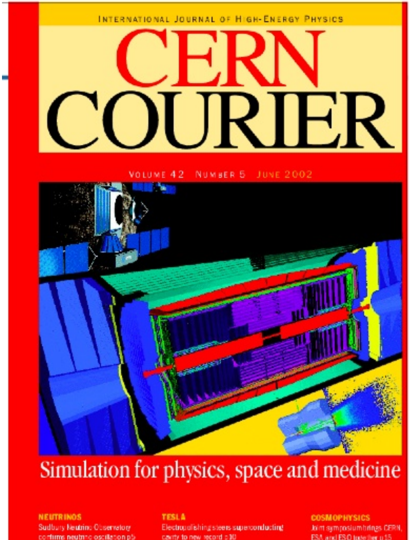
Geant4

Pros:

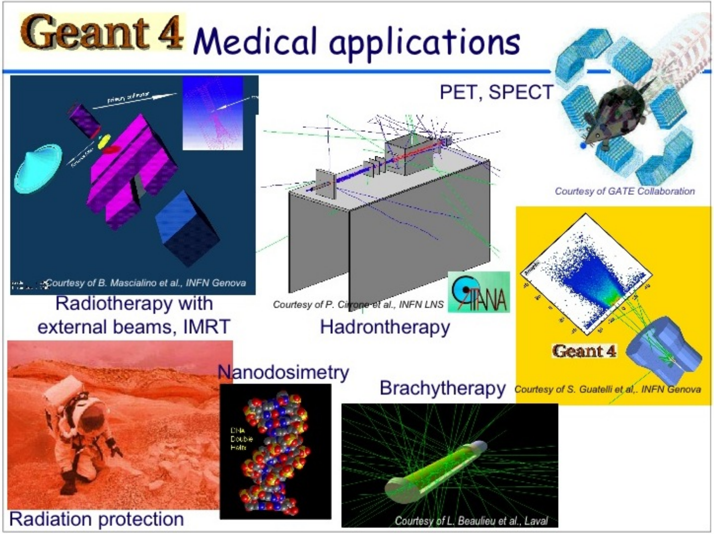
- modular and extensive
- broad applications base

Cons:

- written in C^{++}
- not v. user-friendly



Geant4


Geant 4 Medical applications
PET, SPECT
Courtesy of GATE Collaboration
Courtesy of B. Mascialino et al., INFN Genova
Radiotherapy with external beams, IMRT
Courtesy of P. Cirrone et al., INFN LNS
Hadrontherapy
Geant 4
Courtesy of S. Guatelli et al., INFN Genova
Nanodosimetry
Brachytherapy
DNA Double Helix
Courtesy of L. Beaulieu et al., Laval
Radiation protection

Geant4 vs. EGSnrc

(see e.g. Poon & Verhaegen 2005, *Accuracy of the photon and electron physics in GEANT4 for radiotherapy applications*, Med. Phys. 32, 1696)

- time-dependent geometries in G4 $\Rightarrow$ dynamic IMRT and organ motion studies
- more extensive paticle physics in G4 $\Rightarrow$ hadrontherapy
- G4 optical physics, no explicit energy cutoffs
- most significant discrepancies arise from electron transport (stopping powers, step-size)

Clinical implementation?

Chetty I. +. Med. Phys. 34(12), 4818, Dec. 2007.

Report of the AAPM Task Group No. 105: Issues associated with clinical implementation of Monte Carlo-based photon and electron external beam treatment planning

- speed vs. accuracy:

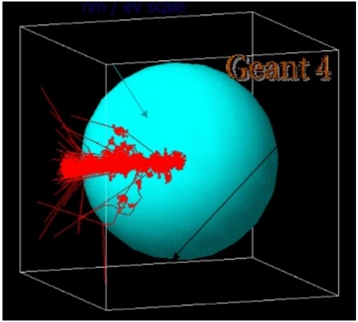
$$\text{efficiency} \propto \frac{1}{t_{\text{cpu}}\sigma^2}$$

- optimisation depends on:
  - physics approximations
  - variance reduction techniques
  - transport parameters

Nanodosimetry

- quantifying health risks due to radiation exposure is challenging – need to model biological effects of radiation on DNA-scales
- implications for radiation therapy, radiation protection
- new G4-DNA code (beta release) provides framework to simulate additional physical, biological and chemical processes

- liquid H_2O sphere – no cellular structure
- $d = 200\,\mathrm{nm}$
- 1000 x 20 keV e^-s
- scattering, excitation, ionisation cross-sections are still poor approximations



Summary

- Monte Carlo is an exceptionally versatile numerical tool
- can simulate reality!
- sophisticated radiation transport code development for medical physics: EGSnrc and Geant4
- new challenges: clinical implementation and nanodosimetry

The true logic of this world is in the calculus of probabilities. *(James Clerk Maxwell)*