GATE-RT
Applications in Radiation Therapy

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GATE-RT: Radiation Therapy applications

- Related to dose distribution
- Radiotherapy: therapy with photon
- Hadrontherapy: therapy with hadron (Proton, Carbon)

Other radiation simulations
- Brachytherapy
- Dose during X-Ray imaging
- Research experiments (biology, physics)
- ...

- ...
Radiation Therapy

Simulated with GATE

Photon beam(s)

Target (CT)

Output = dose distribution
Photon Beam: LINAC

Diagram showing the components of a LINAC system, including the primary electron source, target, primary collimator, flattening filter, ionizing chamber, backscatter-plate, mirror, multi-leaf collimator (MLC), Y backup, X collimator, and output screen.
Simulation vs Measurements

[Grevillot et al, PMB, 2011]
Proton beam

Cyclotron

The IBA Pencil Beam Scanning dedicated nozzle
Simulation vs Measurements

98.71 MeV proton beam in water

Difference lower than 2%

[Grevillot et al, NimB, 2010]
In-beam Hadron-PET

- Carbon beam
- Nuclear fragment
- B+ emitters
- Back to back photon
- Dose monitoring!

Simulation of both dose distribution and imaging
Gate potentialities

- Set of multi-purpose **tools**
  - Dose measurement
  - Physics list: lot of processes/models
  - Phase-Space management (read/write)
  - Some specific particles sources
  - Very flexible: highly tunable
- To be adapted for your system
- Evolving toolkit:
  - advanced users (C++) can add new functionalities
Lecture (this presentation)

Too long. Serve as reference. Please consult it.

Practical Exercises


http://tinyurl.com/3cv6yta

PE7_1 : beam in waterbox

PE7_2 : phase-space with linac head

PE7_3 : proton beam in CT
1. Introduction
2. Simulation architecture
3. Macros: geometry, physic lists
4. Macros: Actors & Filters
5. Macros: Sources
6. Macros: Phase-Space
7. Macros: insert a CT
8. Macros: DoseActor
Architecture of a simulation

- Good practices
- Folders organization
  - mac output data
  - Execution from this folder
Architecture of a simulation

- Macros organization
  - All included macro files must be in mac/
    /control/execute mac/physic-list.mac

  - All included data files must be in data/
    /gate/geometry/setMaterialDatabase data/GateMaterials.db

  - All output files must be in output/
    /gate/actor/doseDistribution/save output/dose.root
FILE : simulation1/mac/main.mac

[ Verbose macros ]

1 - Geometry description macros

2 - Physics list related macros

2 - Detectors (output) macros

[ Visualization macros ]

4 - Sources macros

/goto/run/initialize
/goto/application/setTotalNumberOfPrimaries 50
/goto/application/start

At this stage, Geant4 build the geometry and the physics tables

At this stage, Geant4 start the simulation
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## Verbose macros

### GATE verbose

<table>
<thead>
<tr>
<th>Macro</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>/gate/verbose Physic</td>
<td>2</td>
</tr>
<tr>
<td>/gate/verbose Cuts</td>
<td>2</td>
</tr>
<tr>
<td>/gate/verbose SD</td>
<td>0</td>
</tr>
<tr>
<td>/gate/verbose Actions</td>
<td>0</td>
</tr>
<tr>
<td>/gate/verbose Actor</td>
<td>3</td>
</tr>
<tr>
<td>/gate/verbose Step</td>
<td>0</td>
</tr>
<tr>
<td>/gate/verbose Error</td>
<td>0</td>
</tr>
<tr>
<td>/gate/verbose Warning</td>
<td>0</td>
</tr>
<tr>
<td>/gate/verbose Output</td>
<td>0</td>
</tr>
<tr>
<td>/gate/verbose Beam</td>
<td>2</td>
</tr>
<tr>
<td>/gate/verbose Volume</td>
<td>0</td>
</tr>
<tr>
<td>/gate/verbose Image</td>
<td>0</td>
</tr>
<tr>
<td>/gate/verbose Geometry</td>
<td>2</td>
</tr>
<tr>
<td>/gate/verbose Core</td>
<td>0</td>
</tr>
</tbody>
</table>

Useful to debug physics

### GEANT4 verbose

<table>
<thead>
<tr>
<th>Macro</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>/run/verbose</td>
<td>0</td>
</tr>
<tr>
<td>/event/verbose</td>
<td>0</td>
</tr>
<tr>
<td>/tracking/verbose</td>
<td>0</td>
</tr>
</tbody>
</table>

Useful to debug generated primary particles
1. Introduction
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3. Macros: geometry, physic lists
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Geometry macros

Several lists of materials

/gate/geometry/setMaterialDatabase data/GateMaterials.db
/gate/geometry/setMaterialDatabase data/MyMaterials.db

# WORLD
/gate/world/setMaterial Air
/gate/world/geometry/setXLength 2.0 m
/gate/world/geometry/setYLength 2.0 m
/gate/world/geometry/setZLength 2.0 m

# WATERBOX
/gate/world/daughters/name waterTank
/gate/world/daughters/insert box
/gate/waterTank/setMaterial Water
/gate/waterTank/geometry/setXLength 20.0 cm
/gate/waterTank/geometry/setYLength 20.0 cm
/gate/waterTank/geometry/setZLength 20.0 cm
/gate/waterTank/placement/setTranslation 0 0 -10 cm
/gate/waterTank/vis/setColor blue

World is required

Like any others simulations
A physic list is:

- A set of processes (with options)
  If a process is not indicated in the macro, GEANT4 will ignore it.

- A set of « cuts »
  Tradeoff between simulation time/precision.
/gate/physics/addProcess PhotoElectric
/gate/physics/processes/PhotoElectric/setModel StandardModel

/gate/physics/addProcess Compton
/gate/physics/processes/Compton/setModel StandardModel

/gate/physics/addProcess GammaConversion
/gate/physics/processes/GammaConversion/setModel StandardModel

/gate/physics/addProcess ElectronIonisation
/gate/physics/processes/ElectronIonisation/setModel StandardModel e-
/gate/physics/processes/ElectronIonisation/setModel StandardModel e+

/gate/physics/addProcess Bremsstrahlung
/gate/physics/processes/Bremsstrahlung/setModel StandardModel e-
/gate/physics/processes/Bremsstrahlung/setModel StandardModel e+

/gate/physics/addProcess PositronAnnihilation

/gate/physics/addProcess MultipleScattering
Physic lists

• For each process:
  – Several models
  – Several data (cross-section)
  – Several options

Very powerful but can be very confusing

• Advice1: use the proposed PL
• Advice2: read GATE+G4 documentation
• Advice3: share your experience
### Physic lists - hadronic

- Hadron, ion ionisation
- Elastic and inelastic processes
- Still in development

```
gate/physics/addProcess ProtonInelastic
gate/physics/processes/ProtonInelastic/setModel G4BinaryCascade
gate/physics/processes/ProtonInelastic/G4BinaryCascade/setEmin 170 MeV
gate/physics/processes/ProtonInelastic/G4BinaryCascade/setEmax 500 GeV
gate/physics/processes/ProtonInelastic/setModel PreCompound
gate/physics/processes/ProtonInelastic/PreCompound/setEmin 0 MeV
gate/physics/processes/ProtonInelastic/PreCompound/setEmax 170 MeV
```
Physic lists – print for debug

/gate/physics/processList Available
/gate/physics/processList Enabled

/gate/physics/processList [State][Particle]
- **Production cuts:** do not produce secondaries if below threshold

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Region</th>
<th>Cut Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>/gate/physics/Gamma/SetCutInRegion</td>
<td>world</td>
<td>1 mm</td>
</tr>
<tr>
<td>/gate/physics/Electron/SetCutInRegion</td>
<td>world</td>
<td>1 mm</td>
</tr>
<tr>
<td>/gate/physics/Positron/SetCutInRegion</td>
<td>world</td>
<td>1 mm</td>
</tr>
<tr>
<td>/gate/physics/Gamma/SetCutInRegion</td>
<td>waterTank</td>
<td>0.1 mm</td>
</tr>
<tr>
<td>/gate/physics/Electron/SetCutInRegion</td>
<td>waterTank</td>
<td>0.1 mm</td>
</tr>
<tr>
<td>/gate/physics/Positron/SetCutInRegion</td>
<td>waterTank</td>
<td>0.1 mm</td>
</tr>
</tbody>
</table>

- Particles are tracked until the limits of the model

- **Other limits:**

<table>
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<tr>
<th>Configuration</th>
<th>Region</th>
<th>Cut Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>/gate/physics/SetMaxStepSizeInRegion</td>
<td>waterTank</td>
<td>0.01 mm</td>
</tr>
<tr>
<td>/gate/physics/displayCuts</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
1. Introduction
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8. Macros: DoseActor
Detectors: the ACTORS

- “Actor” concept:
  - Generate output
  - But can also influence the simulation

- Example of actors
  - DoseActor: store deposited dose
  - SimulationStatisticActor: store number or Event, track, steps
  - KillActor: kill a particle when passing through a volume
  - TrackLengthActor: store the length of a track
  - EnergySpectrumActor: store energy distribution
  - ProductionAndStoppingActor: store positions of produced secondaries
  - PhaseSpaceActor: to store a phase space
• Actor common interface

/gate/actor/addActor  [Actor Type]  [Actor Name]
/gate/actor/[Actor Name]/attachTo  [Volume Name]
/gate/actor/[Actor Name]/save  [File Name]
/gate/actor/[Actor Name]/saveEveryNEvents  [N]
/gate/actor/[Actor Name]/saveEveryNSeconds  [N]

/gate/actor/addActor  EnergySpectrumActor  MyActor
/gate/actor/MyActor/attachTo  MyWaterBox
/gate/actor/MyActor/energySpectrum/setEmin  0 eV
/gate/actor/MyActor/energySpectrum/setEmax  10 GeV
/gate/actor/MyActor/energySpectrum/setNumberOfBins  200
/gate/actor/MyActor/save   output/MyOutputFile.root
• Output file format
  – Depends on the actor type
  – Often ROOT files, txt file
• [www.root.cern.ch](http://www.root.cern.ch)
• Important: only activated for particles inside the attached volume
• For advanced users:
  – Write your own Actor (C++)
  – Like a plugin: only add your files (MyActor.hh and MyActor.cc) and compile
  – Share with colleagues!
Filters

- To be combined with an actor: used to select particles
- Several types of filter

```
gate/actor/addActor KillActor MyActor
/gate/actor/MyActor/save output/MyOutputFile.txt
/gate/actor/MyActor/attachTo MyVolume
```

```
gate/actor/MyActor/addFilter particleFilter
gate/actor/MyActor/particleFilter/addParticle e-
gate/actor/MyActor/particleFilter/addParticle e+
```

```
gate/actor/addActor KillActor MyActor
/gate/actor/MyActor/save output/MyOutputFile.txt
/gate/actor/MyActor/attachTo MyVolume
```

```
gate/actor/MyActor/addFilter energyFilter
gate/actor/MyActor/energyFilter/setEmin 5 MeV
```
Remember

- Every **Volume** has a type and a name
  - Examples of types: Box, Sphere ...

- Every **Actor** has a type and a name
  - Attached to a **Volume**
  - Examples of types: DoseActor, KillActor ...

- Every **Filter** has a type and a name
  - Attached to an **Actor**
  - Examples of types: energyFilter, particleFilter

- You could add (and combine) numerous volume, actors and filters
- Each type has specific options
Lecture (this presentation)
  Too long. Serve as reference. Please consult it.

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• Several type of source. One is GPS.

• General Particle Source (GPS)
  • See doc on the wiki

• Simple parameterized source
  – *Type* of primaries particle: g, e+, p ...
  – *Energy*: monoenergetic, histogram, Gaussian ...
  – *Shape/Position*: box, sphere ...
  – *Direction*: beam like, ...
/gate/source/addSource mybeam gps

/gate/source/mybeam/gps/particle gamma

/gate/source/mybeam/gps/pos/type Plane
/gate/source/mybeam/gps/pos/shape Circle
/gate/source/mybeam/gps/pos/centre 0 0 0 mm
/gate/source/mybeam/gps/pos/radius 3 mm

/gate/source/mybeam/gps/direction 0 0 1

/gate/source/mybeam/gps/ene/type Gauss
/gate/source/mybeam/gps/ene/mono 18 MeV
/gate/source/mybeam/gps/ene/sigma 1.0 MeV
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Phase-Space

- How to create? Specific Actor
- How to use? Specific Source
- How to store? ROOT / AIEA (limited)
Phase-Space: creation

PhaseSpaceActor

```
/gate/actor/addActor PhaseSpaceActor MyPS
/gate/actor/MyPS/attachTo MyVolume
/gate/actor/MyPS/save output/MyPS.root
/gate/actor/MyPS/useVolumeFrame
/gate/actor/MyPS/storeSecondaries false
/gate/actor/MyPS/storeOutgoingParticles
/gate/actor/MyPS/enableParticleName true
/gate/actor/MyPS/enableProductionVolume true
/gate/actor/MyPS/enableProductionProcess true
```
Phase-Space: use

- Need to create an attached volume first
- Can use less particles than stored in the Phase-Space

/gate/source/addSource MyBeam phaseSpace
/gate/source/MyBeam/addPhaseSpaceFile output/MyPS.root
/gate/source/MyBeam/attachTo PhS_Plane
Phase-Space: file format

- **Root file**
  - Automatically split into 2Gb files
  - Very flexible
  - Can be analyze with Root

- **AIEA file**
  - Standard but limited
Outline

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Insert a CT image

- **Step 1**: convert Dicom image to Analyze image file format
- **Step 2**: define HU to materials conversion
- **Step 3**: insert image with macro
Step1: convert DICOM to HDR

- HDR/IMG : *Analyze* image file format
- An image is stored with 2 files
  - Header: *myImage.hdr*
  - Raw data: *myImage.img*
- Use the VV software
  - Open dicom
  - Save as
  - Image can resampled (2mm for example)
- [vv.creatis.insa-lyon.fr](http://vv.creatis.insa-lyon.fr)
Image coordinate system

Image:
• Resolution: 512 x 512 x 120
• Spacing: 0.9 x 0.9 x 2 (mm)
• PixelType: float or unsigned short
• Origin: coord of the first pixel in « physical coordinate » (mm)
• Orientation: associated matrix

GATE DOES NOT TAKE origin/orientation into account !!
Step 2: stoichiometric calibration

- Macros to generate HU <-> material
  - Generate a list of materials
  - Generate a list of HU to material name correspondence

/gate/HounsfieldMaterialGenerator/SetMaterialTable data/MaterialsTable.txt
/gate/HounsfieldMaterialGenerator/SetDensityTable data/DensitiesTable.txt
/gate/HounsfieldMaterialGenerator/SetDensityTolerance 0.1 g/cm³
/gate/HounsfieldMaterialGenerator/SetOutputMaterialDatabaseFilename data/myimage-HUmaterials.db
/gate/HounsfieldMaterialGenerator/SetOutputHUMaterialFilename data/myimage-HU2mat.txt
/gate/HounsfieldMaterialGenerator/Generate
Step 3: insert image as volume

```
/gate/world/daughters/name    patient
/gate/world/daughters/insert  ImageNestedParametrisedVolume
/gate/patient/geometry/SetImage data/myimage.hdr
/gate/geometry/setMaterialDatabase data/myimage-HUmaterials.db
/gate/patient/geometry/SetHUToMaterialFile data/myimage-HU2mat.txt
/gate/patient/placement/setTranslation 0 0 0 mm
```
CT insertion, other options

- Alternative navigator:
  - Faster in some situation
  - Use "ImageRegionalizedVolume" instead of "ImageNestedParametrisedVolume"

- Stoichiometric calibration: you need to calibrate your CT [Schneider et al 2000]

- Image file format will be improved.
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DoseActor

- Store deposited dose in a **3D** matrix
- Can be used also for **1D** and **2D** dose map
- Can store: dose, edep, nb of hits
- Compute associated **statistical uncertainty**
- Size and resolution of the matrix can be specified
- Need to be attached to a volume (that can be voxelized or not)
- You can use any DoseActor, attached to the same volume or to different ones
```plaintext
/gate/actor/addActor   DoseActor  doseDistribution
/gate/actor/doseDistribution/attachTo   MyVolume
/gate/actor/doseDistribution/stepHitType random
/gate/actor/doseDistribution/setPosition 0 0 0 mm
/gate/actor/doseDistribution/setVoxelSize 2 2 2 mm
/gate/actor/doseDistribution/saveEveryNSeconds 60
/gate/actor/doseDistribution/enableEdep true
/gate/actor/doseDistribution/enableUncertaintyEdep true
/gate/actor/doseDistribution/enableDose true
/gate/actor/doseDistribution/enableNumberOfHits true
```
• Only store what happened in the attached volume, even if the size of the DoseActor is larger
• We call « dosel » the volume where is stored the dose
• Can be different from the « voxel » size of the associated image (but it is not really recommended).
• Store the dose in the dosel that contains a point randomly chosen on the step segment
Output file format:
- **TXT** (ASCII files): only for 1D distribution (not really recommended)
- **Root**: for 1D or 2D distribution
- **HDR/IMG** image (Analyze): for 3D distribution
- Need specific tools to analyze such output
DoseActor: statistical uncertainty

- See [Chetty et al IJROBP 2006]
  - Reporting and analyzing **statistical uncertainties** in Monte Carlo-Based Treatment Planning

**Statistical uncertainty in dose in the voxel** \( k \)

\[
\sigma_{d_k} = \sqrt{\frac{1}{N - 1} \left( \frac{\sum_{i=1}^{N} d_{k,i}^2}{N} - \left( \frac{\sum_{i=1}^{N} d_{k,i}}{N} \right)^2 \right)}
\]

**Relative percentage uncertainty in the dose per voxel**

\[
\epsilon_k = 100 \times \frac{S_k}{D_k}
\]
DoseActor: statistical uncertainty

- If the simulation is split into **multiple jobs**
  - Global statistical uncertainty **CANNOT** be computed from the uncertainties of each job
  - Instead, use SquaredDose
    
    ```
    /gate/actor/addActor DoseActor doseDistribution
    ...
    /gate/actor/doseDistribution/enableDose true
    /gate/actor/doseDistribution/enableSquaredDose true
    ```

- Then merge (addition) all output files and compute the equation.
- Tools are not (yet) provided in the Gate release. Available in VV as test. Will be provided in future release.
Advanced features

- Motion and time management
  - **Repeater**: to duplicate volume (e.g. multi-leafs collimator)
  - **Mover**: displace volume or source according to time
  - Both together

```plaintext
/gate/mybox/repeaters/insert genericRepeater
/gate/mybox/genericRepeater/setPlacementsFilename data/mybox.pls
/gate/mybox/genericRepeater/useRelativeTranslation 1

/gate/mybox/moves/insert genericMove
/gate/mybox/genericMove/setPlacementsFilename data/mybox_move.pls

/gate/mybox/moves/insert genericRepeaterMove
/gate/mybox/genericRepeaterMove/setPlacementsFilename data/mybox_mov_rep.pls
/gate/mybox/genericRepeaterMove/useRelativeTranslation 1
```
Conclusion

- Gate is
  - A set of tools
  - A community (site, mailing list)
- Read documentation
- Improve documentation (wiki)
- Evolving code
- Advanced usage: C++
THANK YOU FOR YOUR ATTENTION

Thibault Frisson, Nabil Zahra, Loic Grevillot, Pierre Gueth, David Sarrut