PHYSICS OVERVIEW AND PROCESSES

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Outline

- Physics Overview
  - the physics Geant4 has to offer
- Processes
  - how they work
  - example processes
- Production thresholds

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Physics overview

Geant4 physics

- Geant4 provides a wide variety of physics components for use in simulation
- Physics components are coded as processes
  - a process is a class which tells a particle how to interact
  - user may write his own processes
    - derived from Geant4 process
- Processes are grouped into
  - electromagnetic, hadronic, and decay categories

Geant4 Physics: Electromagnetic

- standard – complete set of processes covering charged particles and gammas
  - energy range 1 keV to ~PeV
- low energy – specialized routines for e-, gammas, charged hadrons
  - more atomic shell structure details
  - some processes valid down to 250 eV or below
  - others not valid above a few GeV
- optical photon – only for long wavelength photons (x-rays, UV, visible)
  - processes for reflection/refraction, absorption, wavelength shifting, Rayleigh scattering

Geant4 Physics: Hadronic

- Pure hadronic (0 - ~TeV)
  - Elastic
  - Inelastic
  - Capture
  - Fission
- Radioactive decay
  - at-rest and in-flight
- Photo-nuclear (~10 MeV - ~TeV)
- Lepto-nuclear (~10 MeV - ~TeV)
  - e+, e- nuclear reactions
  - muon-nuclear reactions

Geant4 Physics: decay and parameterized

- Decay processes include
  - weak decay (leptonic decays, semi-leptonic decays, radioactive decay of nuclei)
  - electromagnetic decay (π^0, Σ^0, etc. decay)
  - strong decays not included here
    - they are part of hadronic models
- Parameterized processes
  - electromagnetic showers are propagated according to parameters averaged over many events
  - faster than detailed shower simulation

Physics processes

Physics processes (1)

- All the work of particle decays and interactions is done by processes
  - transportation is also handled by a process
- A process does two things:
  - decides when and where an interaction will occur
    - method: GetPhysicalInteractionLength()
    - this requires a cross section, decay lifetime
    - for the transportation process, the distance to the nearest object along the track is required
  - generates the final state of the interaction (changes momentum, generates secondaries, etc.)
    - method: DoIt()
    - this requires a model of the physics

Physics processes (2)

- There are three flavors of processes:
  - well-located in space → PostStep
  - distributed in space → AlongStep
  - well-located in time → AtRest
- A process may be a combination of all three of the above
  - in that case six methods must be implemented (GetPhysicalInteractionLength() and DoIt() for each action)
- "Shortcut" processes are defined which invoke only one
  - Discrete process (has only PostStep physics)
  - Continuous process (has only AlongStep physics)
  - AtRest process (has only AtRest physics)

Example processes (1)

- Discrete process: Compton Scattering
  - step determined by cross section, interaction at end of step
    - PostStepGPIL()
    - PostStepDoIt()
- Continuous process: Cerenkov effect
  - photons created along step, # roughly proportional to step length
    - AlongStepGPIL()
    - AlongStepDoIt()
- At rest process: positron annihilation at rest
  - no displacement, time is the relevant variable
    - AtRestGPIL()
    - AtRestDoIt()
- These are examples of so-called “pure” processes

Example processes (2)

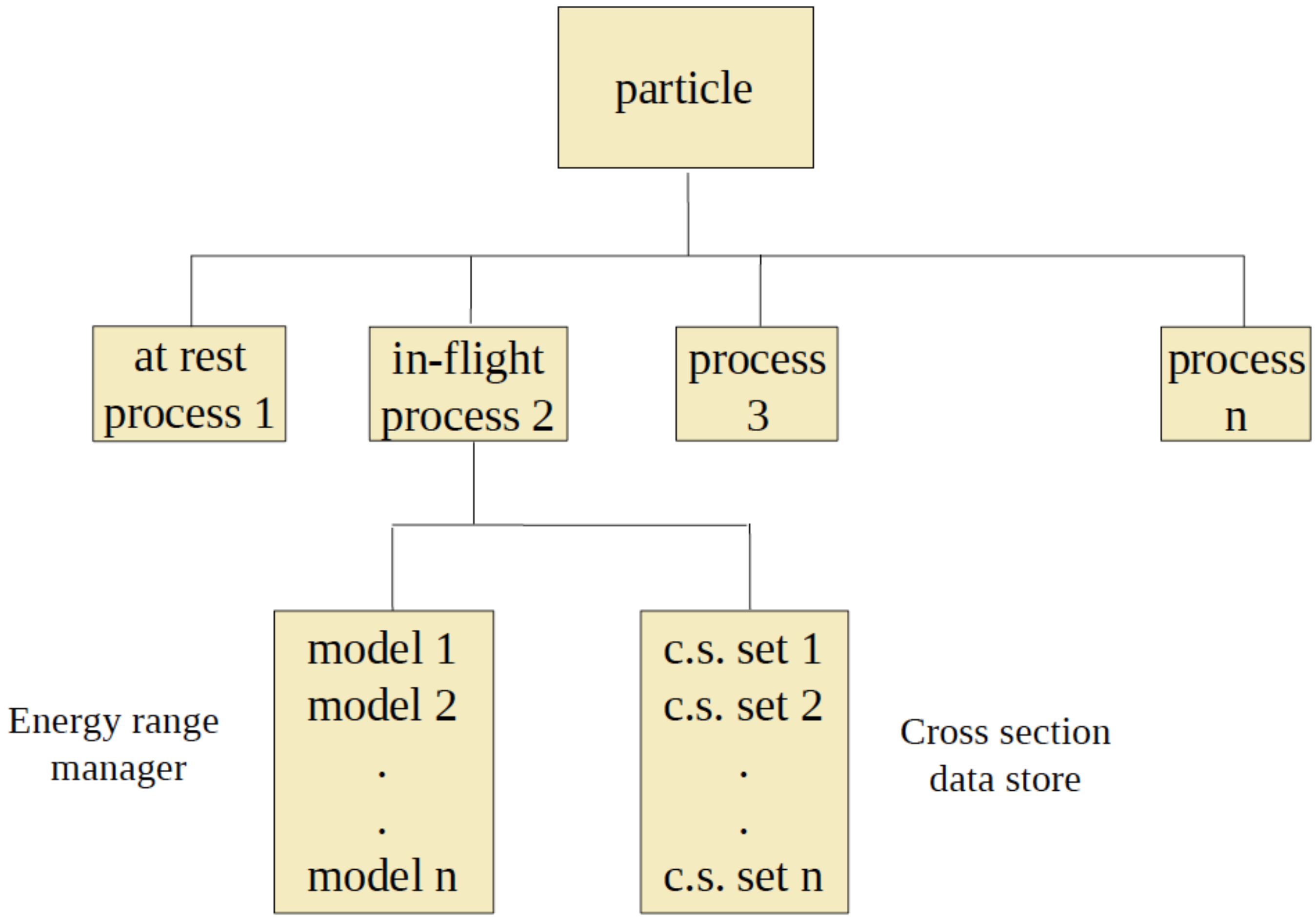
- Continuous + discrete: ionization
  - energy loss is continuous
  - Moller/Bhabha scattering and knock-on electrons are discrete
- Continuous + discrete: bremsstrahlung
  - energy loss due to soft photons is continuous
  - hard photon emission is discrete
- In both cases, the production threshold separates the continuous and discrete parts of the process
  - more on this later
- Multiple scattering is also continuous + discrete

Handling multiple processes

- Many processes (and therefore many interactions) can be assigned to the same particle

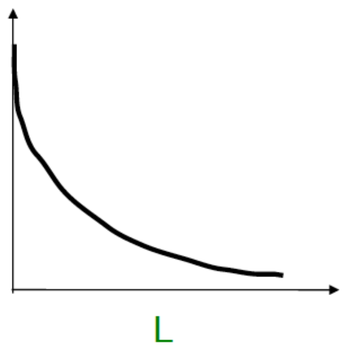
- How does Geant4 decide which interaction happens at any one time?
  - interaction length or decay length is sampled from each process
  - shortest one happens, unless
    - a volume boundary is encountered in less than the sampled length. Then no physics interaction occurs (just simple transport).
  - the processes that were not chosen have their interaction lengths shortened by the distance travelled in the previous step
  - repeat the procedure

Handling multiple processes



Interaction length sampling

- At the beginning of the first step, the interaction length is found from the cross section and target number density:
  - sampling is done from the distribution $e^{-\sigma \rho L}$



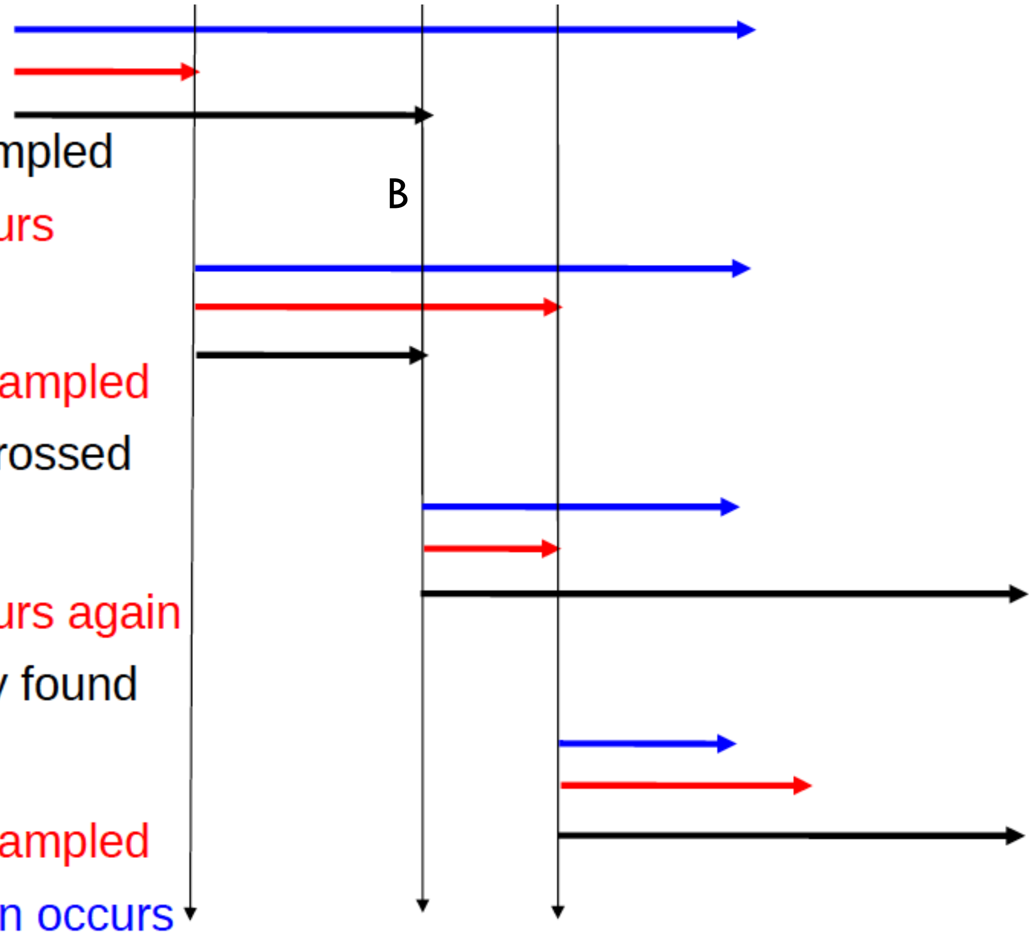
- this is done for each process assigned to the particle, so we now have several different lengths, plus the distance to the next volume boundary

Which process occurs ?

- For the simple case of a gamma with Compton scattering and pair production assigned, the sampled lengths will be:
  - typically short for Compton scattering (large cross section)
  - typically long for pair production (small cross section)
- The process with the shortest sampled length is always chosen to occur
  - this process defines the length of the first step
- After the process occurs, we're ready for the next step
  - the process which has just occurred must be re-sampled
  - the processes which did not occur (pair production) are not re-sampled and must have the previous step length subtracted from their originally sampled lengths

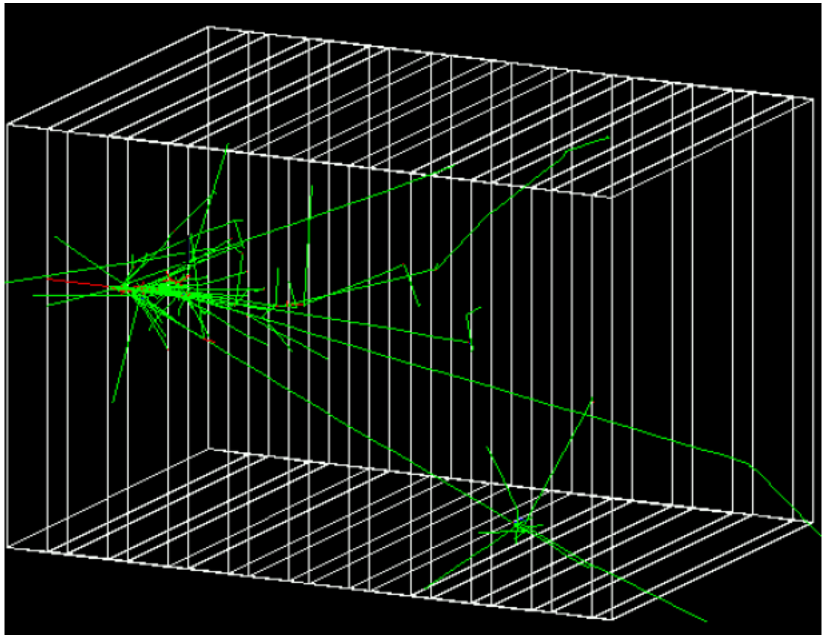
Which process occurs ?

- Step 1:
  - all lengths sampled
  - Compton occurs
- Step 2:
  - Compton re-sampled
  - boundary is crossed
- Step 3:
  - Compton occurs again
  - new boundary found
- Step 4:
  - Compton re-sampled
  - pair production occurs



Example Event with Standard EM Processes Turned On

- 50 MeV e- entering LAr-Pb calorimeter
- Processes used
  - bremsstrahlung
  - ionization
  - multiple scattering
  - positron annihilation
  - pair production
  - Compton scattering



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Production threshold

Secondary production threshold

- Every simulation developer must answer the question: how low in energy can you go?
  - at what energy do I stop tracking particles ?
- This is a balancing act
  - need to go low enough to get the physics you're interested in
  - can't go too low because some ϕ processes have infrared divergences causing CPU time to explode
    - eg. Bremsstrahlung, delta-rays production
- The traditional Monte Carlo solution is to impose an absolute cutoff in energy (eg. Geant3)
  - particles are stopped when this energy is reached
  - remaining energy is dumped at that point

Secondary production threshold

- But, such an absolute cut-off in energy may cause imprecise stopping location and deposition of energy
- There is also a particle dependence
  - the range of 10 keV gammas in Si is a few cm
  - different from the range of 10 keV e- in Si which is a few microns
- And a material dependence, eg sampling calorimeter:
  - suppose you have a detector made of alternating sheets of Pb and plastic scintillator
  - you set cut-off for Pb, it will likely be wrong for scintillator which does the actual energy deposition measurement
  - you set cut-off for scintillator, Geant4 will spend excessive time tracking shower particles in Pb

Secondary production threshold

- In Geant4 there are no tracking cuts
  - particles are tracked down to a zero range/kinetic energy
- Only production thresholds exist
  - i.e. cuts allowing a particle to be created or not
- Why are such cuts needed ?
  - Some electromagnetic processes involve infrared divergences
  - this leads to a huge number of smaller and smaller energy photons/electrons (such as in Bremsstrahlung, δ-ray production)
  - production cuts limit this production to particles above the threshold only
  - the remaining, divergent part, is treated as a continuous effect (i.e. AlongStep action)

Secondary production threshold

- Geant4 solution: impose a cut in range
  - default value is 1 mm, you can set yours in your PhysicsList
  - the primary particle loses energy by producing secondary electrons or gammas
  - if the primary no longer has enough energy to produce secondaries which travel at least this cut in range (1 mm), two things happen:
    - the discrete energy loss ceases: no more secondaries are produced
    - the primary is tracked down to zero energy using continuous energy loss
- Stopping location is therefore correct
- Only one value of cut in range is needed for all materials because it corresponds to different production thresholds in energy (depending on material).

Summary

- Geant4 supplies many physics processes which cover electromagnetic, hadronic and decay physics
- Processes are organized according to when they are used during the tracking of a particle (discrete, continuous, at-rest, etc.)
- Many processes may be assigned to one particle
  - which one occurs first depends on cross sections, lifetimes, and distances to volume boundaries

Thank you for your attention