Outline

• Physics Overview
  ▪ the physics Geant4 has to offer

• Processes
  ▪ how they work
  ▪ example processes

• Production Thresholds
  ▪ setting the boundary between discrete and continuous energy loss
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-, γ, 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 ($\pi^0$, $\Sigma^0$, etc. decay)
  - strong decays not included here (they are part of hadronic models)

- Parameterized processes
  - electromagnetic showers propagated according to parameters averaged over many events
  - faster than detailed shower simulation
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
  ▪ detailed discussion of this in next talk
particle

- at rest process 1
- in-flight process 2
- process 3
- process n

Energy range manager

- model 1
- model 2
- .
- model n

Cross section data store

- c.s. set 1
- c.s. set 2
- .
- c.s. set n
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
Threshold for Secondary Production

- Every simulation developer must answer the question: how low can you go?
  - at what energy do I stop tracking particles?

- This is a balancing act:
  - go low enough to get the physics you're interested in
  - can't go too low because some processes have infrared divergence causing CPU time to skyrocket

- The traditional Monte Carlo approach is to impose an absolute cutoff in energy
  - particles are stopped when this energy is reached
  - remaining energy is dumped at that point
Threshold for Secondary Production (2)

- But such a cut could cause imprecise stopping location and deposition of energy

- There is also a particle dependence:
  - range of 10 keV $\gamma$ in Si is a few cm
  - range of 10 keV e- in Si is a few microns

- And a material dependence:
  - suppose you have a detector made of alternating sheets of Pb and plastic scintillator
  - if the cutoff is OK for Pb, it will likely be wrong for the scintillator which does the actual energy deposition measurement
Threshold for Secondary Production (3)

- Geant4 solution: impose a **production threshold**
  - this threshold is **distance**, not an energy
  - default = 1 mm
  - the primary particle loses energy by producing secondary electrons or gammas
  - if primary no longer has enough energy to produce a secondary which travels at least 1mm, two things happen:
    - discrete energy loss ceases (no more secondaries produced)
    - the primary is tracked down to zero energy using continuous energy loss
- Stopping location is therefore correct
- Only one value of production threshold distance is needed for all materials because it corresponds to different energies depending on material
Production Threshold vs. Energy Cut

500 MeV p in LAr-Pb sampling calorimeter

Cut = 2 MeV

Cut = 450 keV

Production range = 1.5 mm
Threshold for Secondary Production (4)

- Geant4 recommends the default value of 1 mm
  - user needs to decide best value
  - this will depend on the size of sensitive elements within the simulated detector, and on available CPU
- The value is set in the SetCuts() method in your physics list
- Instead of “secondary production threshold distance” it is simply more convenient to say “cuts”
  - but please remember that this does not mean than any particle is actually stopped before it runs out of energy
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.

- Geant4 implements secondary particle production thresholds by means of a single distance:
  - all particles are tracked down to zero energy.
How Geant4 Handles Competing Processes
(addendum to Process Overview talk)
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 $e^{-\sigma_{p}L}$

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
Reducing the Interaction Lengths

- **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