CHAPTER 1

Electron Gamma Shower
-EGS

Exerted from: http://www2.slac.stanford.edu/vvc/egs

About EGS

When high-energy particles, in the form of electrons and/or photons hit matter, they travel through the material, interacting with atoms and their nuclei in various ways that are easily predicted by physics. The path of each particle can be modeled as a "random walk" as collisions with atoms occur with well-defined probability.

Each individual interaction can generate many more electrons and photons due to collisions as it travels through matter. This process is given the name "shower" because that is what it looks like. The picture above is a computer simulation, generated using the EGS code, showing the interactions generated by a single 1 GeV electron hitting a 2 cm thick
EGS was developed to design safe experiments for high energy physics. By modeling these processes physicists could ensure that the shielding they installed would protect everyone around from the short-lived but intense radiation produced when an accelerator beam strikes a target. The same EGS code has been used to design detectors of this radiation and it was used in the design of most of the particle physics experiments in the 1980s.

The EGS code is capable of generating many kinds of pictures. The image above is an example showing 10 high-energy positrons (300 MeV) spread out vertically and incident from the left into liquid hydrogen in a 1-Tesla magnetic field going into the screen. Again, electrons are green, positrons are red and photons are yellow. The trajectories of the electrons are bent into spirals because of the magnetic field that is perpendicular to the page and electrons and positrons spiral in opposite directions. Photons are not affected by magnetic fields. Look at all the particles set in motion from just a few high-energy positrons!

Did you know that a magnet in your TV bends low-energy electrons to different areas of your screen to create an image?

As you could guess, predicting the combined effect of all the interactions in this process is extremely difficult using standard mathematical methods . . . but the EGS code can do it!

**History of EGS**

The "seed" for the EGS computer program was brought to SLAC around 1965 by Hans-Hellmut Nagel of Bonn University. Nagel's program was useful in designing elements of accelerator machinery (such as beam stoppers, collimators, and targets) during construction of the two-mile accelerator and beam lines at SLAC. However, Nagel's code proved to be too specific to solve many problems still facing the high-energy physics community.
Introduction

Two physicists took on the task of redesigning the code from the bottom up to achieve the necessary generalization. Working independently at first, W. Ralph Nelson at SLAC, and later Richard Ford at the Hanson High Energy Physics Laboratory on the Stanford University campus, decided to combine their programming efforts and produced the first version of EGS in 1978.

The Electron Gamma Shower (EGS) Code System (or EGS3, as it was known at that time) was designed to simulate the flow of electrons and photons through matter at energies ranging from just below an MeV to several thousand GeV. EGS uses a statistical game-playing approach to solve the difficult mathematical problem posed by electron transport through matter. The program uses Monte Carlo (game-playing) methods to simulate the statistical outcome of each interaction. All possible outcomes of an interaction are identified and assigned to an imaginary roulette wheel and the wheel is weighted to reflect predicted outcomes of an interaction. The wheel is spun and particles are created and transported in a random-walk process.

This version of EGS proved valuable in detector design, radiation shielding analysis, determining accelerator component temperature rises, and other accelerator problems. EGS, which was well documented, user-friendly, versatile, upwardly-compatible and supported by technical experts, was licensed free of charge to the scientific community. The program soon became very popular and a large user community developed.

Applications

In the early 1980s, several simultaneous events lead to development of the current version of EGS.

The SLAC Radiation Physics Department began working with their counterpart at KEK (Hideo Hirayama) in Japan to extend the flexibility of EGS, with special focus on design of future high-energy accelerators.

A detailed low-energy benchmarking project was underway at the National Research Council of Canada (NRCC). This project, led by Dave Rogers, involved adopting EGS for use as a theoretical tool in ionizing radiation standards to serve the low-energy radiation protection (such as for diagnostic x-ray) and radiotherapy communities.
Scientists outside the field of high-energy physics started using the code to solve low-energy problems, such as those found when using x-rays in medical applications. However, limitations were found when applying EGS to solve low-energy problems.

Radiotherapy treatments were changing from use of relatively low-energy Cobalt-60 gamma rays (about 1.25 MeV) to the radiation produced by higher energy electron linear accelerators (4 - 50 MeV). At these higher energy levels, electron transport complicates dose calculations, and medical physicists needed a tool to predict the correct treatment dose.

As a result of these events, a collaboration was formed between SLAC, KEK and NRCC that lead to the release of the EGS Code System Version 4 (EGS4) in 1985. This latest version of the code is a general-purpose package that uses Monte Carlo simulations to calculate the effect of coupled transport of electrons and photons in an arbitrary geometry for particles with energies above a few keV and up to several TeV - a much wider energy range than the previous version of the code.

Interest in EGS by medical physicists has been overwhelming and worldwide. Almost daily, requests for the program are received and more than 4,000 copies have been distributed to date. More than 80 percent of the requests come from scientists working in medically-related fields. Because EGS was designed to calculate electron transport effects, an experiment was designed to see if the code would, in fact, predict the dose alterations expected by discontinuities, such as those encountered in the human body. The experiment was performed using an air or aluminum cylinder in a water tank, which was then exposed to a beam from a 20 MeV accelerator. The results clearly showed that EGS predicted the dose alterations caused by discontinuities (air/water or air/aluminum interfaces) downbeam from the radiation. This experiment gave medical physicists confidence in the ability of EGS to simulate passage of electrons through the human body.

**The Future**

The EGS Code System is now used by thousands of medical physics researchers to estimate how much energy from the medical accelerators is being deposited in cancer cells during radiotherapy. Maximizing dose to the tumor while minimizing dose to healthy tissues makes radiotherapy more effective, thus saving lives. This subfield of medical physics is called radiotherapy treatment planning and the use of EGS is widely accepted in this field as the most accurate method for doing calculations involving electrons and photons.
EGS is also finding use in a wide variety of medical and biological fields:

- Determining dose distributions from radionuclides used in radioimmunotherapy (monoclonal antibody studies).
- Modeling the Compton effect and attenuation in reconstructed images of brain-blood flow.
- Calculating organ doses received during fluoroscopic examinations.
- Subsurface imaging of agricultural produce with x-rays.
- Defining accurate Iridium-wire implant dosimetry.
- Improving Iodine-125 (and other) brachytherapy methods.
- Tracing the movement of beta emitters after injection into arthritic joints.
- Designing accelerator targets, field-flattening compensators, jaws and other devices used with clinical accelerators.
- Calculating dose distributions in CAT-scan slices of the body.
- Designing methods used in stereotactic surgery.
- Simulating silicon microstrip mammography.
- Calculating the production of radioisotopes (radionuclides) by electron accelerators.
- Simulating PET and SPECT systems to define intrinsic limitations.
- Studying space radiation effects.
- Developing ion chamber correction factors in radiation dosimetry.

Since 1985, the focus on low-energy improvements to EGS have directly benefited the high-energy community. Calorimetry, for example, requires measuring electron-photon showers until the radiation is greatly degraded in energy. Using an EGS option developed by Alex F Bielajew (aka BLIF) and Dave Rogers called Parameter Reduced Electron-Step Transport Algorithm (PRESTA), physicists can now accurately simulate low energy electron transport. This has proved valuable in design of calorimeters.
More recently, a powerful application software package, based on EGS4 and referred to more simply as BEAM, is being used very successfully to characterize the radiation fields that emanate from the electron accelerators.

**Guided Tour**

EGS to Order" is a simulation tool to show what happens when radiation meets matter. It is important to be able to predict these interactions with precision when you need to:

- Ensure safe shielding around experiments that involve high-energy electrons and photons.
- Design better medical X-ray treatments.
- Design detectors for high-energy physics experiments.

Before going too far in this tour, you might want to learn how and why EGS was developed in the "About EGS" section.

In this tour we will discover the physics interactions that occur between individual photons and electrons. These processes are well understood. However, complexity arises when there are large numbers of interacting particles in a beam and atoms in matter. The EGS simulation accurately predicts outcomes in these complex cases -- it encodes the known physics and the probabilities of interaction in each material type.

**Example EGS simulation image**
The image above is an example of pair production in a magnetic field (perpendicular to the screen). Some of the photons in a beam of 10 photons (yellow lines) interact with matter to produce positrons (red lines) and electrons (green lines).

To understand what is happening in this image (and other simulation images), follow our tour.

- Pictorial Code for Particles
- Simple Two Particle Physics Processes
- Sample EGS Images

1.) Pictorial Code for Particles

As we saw in the introduction, the EGS simulation images (output) is color coded by type of particle (electron, photon, or positron). The diagrams used to describe the interaction in this tour are also color coded. The table below shows the relationship between the EGS simulation images, the diagrams used here, and the traditional Feynman Diagrams that visually describe the particle interaction.

In the color coded diagrams we use dashed lines to indicate any of the following:

<table>
<thead>
<tr>
<th>Particle Type</th>
<th>EGS Output</th>
<th>Feynman Diagrams</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real Electron</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Virtual or bound electron</td>
<td>not shown</td>
<td></td>
</tr>
<tr>
<td>Real photon</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Virtual photon or electron fields in atom</td>
<td>not shown</td>
<td></td>
</tr>
<tr>
<td>Real positron</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Virtual positron</td>
<td>not shown</td>
<td></td>
</tr>
</tbody>
</table>

- Virtual particles
  the intermediate stage in a Feynman diagram

- Bound electrons
  electrons initially bound in matter that can absorb a (virtual) photon and appear as real electrons

- Photons absorbed by or emitted from matter
these represent the interaction of an electron with the intense electromagnetic field inside an atom

In all three of these cases the particles do not satisfy the usual real particle relationship

\[ E^2 = p^2 c^2 + m^2 c^4 \]  \hspace{1cm} (EQ 1)

where \( E \) is energy, \( p \) is momentum, \( m \) is particle mass, and \( c \) is the speed of light.

However, all the real particles shown in actual EGS simulation images do satisfy this relationship.

2.) Simple Two Particle Physics Processes

Using the basic processes shown in Feynman diagrams, one can build a simple set of all basic two-particle processes. Each type of process has a name – often named after the physicist who first described the process.

Feynman Diagrams

Richard Feynman was the physicist who developed the method still used today to calculate rates for electromagnetic and weak interaction particle processes. The diagrams he introduced provide a convenient shorthand for the calculations. They are a code physicists use to talk to one another about their calculations.

In Feynman diagrams (time ordered form):

- Left-to-right in the diagram represents time; a process begins on the left and ends on the right.
- Every line in the diagram represents a particle; the three types of particles in the simplest theory (QED) are:
- Up and down (vertical) displacement in a diagram indicates particle motion, but no attempt is made to show direction or speed, except schematically.
Introduction

- Any vertex (point where three lines meet) represents an electromagnetic interaction; possible vertices are:

<table>
<thead>
<tr>
<th>Image</th>
<th>Description</th>
<th>Particle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>straight line, arrow to the right</td>
<td>electron</td>
</tr>
<tr>
<td></td>
<td>straight line, arrow to the left</td>
<td>positron</td>
</tr>
<tr>
<td></td>
<td>wavy line</td>
<td>photon</td>
</tr>
</tbody>
</table>

- an electron emits a photon
- an electron absorbs a photon
- a positron emits a photon
- a positron absorbs a photon
- A photon produces an electron and a positron (an electron-positron pair)
- An electron and a positron meet and annihilate (disappear), producing a photon
(Notice that all six of these processes are just different orientations of the same three elements.)

- Any diagram which can be built using these parts is a possible process provided:
  1. Conservation of energy and momentum is required at every vertex
  2. Lines entering or leaving the diagram represent real particles and must have \( E^2 = p^2 c^2 + m^2 c^4 \)
  3. Lines in intermediate stages in the diagram represent "virtual particles," which do not need to have the right relationship between \( E, p, \) and \( m, \) but which can never be observed if they do not!

The first thing to realize is that no single vertex diagram represents a possible process - no matter how you try, you cannot satisfy rules (1) and (2) above at the same time for such a process.

The simplest process we can consider is a two particle collision or "scattering" event. Let us start and end the process with one electron and one positron-- only their momenta and energies change in the process:

\[
\begin{array}{c}
  \text{Feynman tells us to draw all possible diagrams. First, lets add one intermediate photon line. We find three time-ordered diagrams:} \\
  \text{(a)} \\
  \text{(b)}
\end{array}
\]

\[
\begin{array}{c}
  \text{(a)} \\
  \text{(b)}
\end{array}
\]
This third diagram (c) is really quite a different process -- it is an intermediate stage with only a photon (a virtual photon) present.

The first two figures (a and b) are just different orientations (time-orderings) of the same event. We use the figure below as a shortcut to show both orientations.

Notice that this diagram does not have time orderings, just a start and stop.

We can also draw more complicated diagrams with more photons, for example:
In fact, we could have any number of photons!

What makes the diagrams useful is that each diagram has a definite complex number quantity -- called an amplitude -- related to it by a set of rules (the Feynman rules). One part of these rules is that there is a multiplication factor of \( \frac{e^2}{\pi} = \frac{1}{137} \) for each photon, so the amplitudes for diagrams with many photons are small, compared to those with only one. The quantity \( e \) here is the electromagnetic coupling or electric charge.

Technically, the Feynman rules give the rate as a power series expansion in the coupling parameter. The technique is only useful when this parameter is small, that is, for electromagnetic or weak interactions but not for strong interactions except at very high energies.

Calculations in QED keeping up to four photons have been made for certain quantities. They give a result that matches experimental data up to the twelfth decimal place!

**a) Real and Virtual Particles**

Because Feynman diagrams represent terms in a quantum calculation, the intermediate stages in any diagram cannot be observed. Physicists call the particles that appear in intermediate, unobservable, stages of a process "virtual particles". Only the initial and final particles in the diagram represent observable objects, and these are called "real particles."

**b) Feynman Rules**

The Feynman Rules for a theory are very simple, but lead to increasingly complicated mathematical expressions as increasingly complicated diagrams are constructed.
The rules for any process are:

Draw all possible diagrams (up to some number of photons, depending on the accuracy desired). Different time-orderings of a given process are represented by the same diagram.

Given the initial momentum and energy, define how momentum and energy flow for each line in the diagram. Where each diagram has a closed loop, there is an arbitrary momentum and energy flow around the loop and we must integrate over all possible choices for these quantities. Each intermediate line in the diagram contributes a factor to the amplitude of \( \frac{1}{(E^2-p^2c^2-m^2c^4)} \) where \( m \) is the appropriate mass for the particle type represented by the line. Note that this says that the more "virtual" the particle represented by a line is, the smaller the contribution of the diagram.

Add the amplitude factors from all possible diagrams to get the total amplitude for the process.

The expected rate for the process can then be calculated -- it is proportional to the absolute value of the total amplitude squared. [Note that this is not the same as the sum of the squares of the absolute values of the individual amplitudes.] For more information on this topic, take a look at the discussion of quantum interference.

c.) Quantum Interference

Another peculiarly quantum property is that the wave-like nature of particles leads to interference effects that violate our usual notions of how probability works. Two processes, which when described in a particle language seem quite distinct, actually represent two different contributions to an overall probability amplitude.

The rule for probability in quantum mechanics is that probability is the square of the absolute value of the relevant probability amplitude.

Two processes that can be distinguished by measurement have separate probabilities, and these probabilities add in the usual way. The peculiarity comes about when the processes are not experimentally distinguishable, despite their different particle-language descriptions.

d.) An Example of Particle Interference
For example, consider the following Feynman diagrams. Both represent a process where an electron and a positron collide and an electron and a positron emerge traveling in different directions (what we call a scattering process).

We can read these diagrams as if they are a pictorial representation of a particle process that starts at the left and ends at the right of the picture.

In the first diagram, the electron emits a photon and the positron absorbs it, thus changing the direction of both.

In the second diagram, the electron and positron meet and annihilate, or disappear. For a short time there is only a single virtual photon present, which then disappears to produce a new electron and positron pair, traveling apart in different directions from the initial pair.

These two pictures, and the words we use to "describe" what they represent, certainly appear to be two very different processes. But, we do not observe the intermediate stages and cannot do so without changing the outcome of the experiment.

**e.) The Mathematics of Interference Calculations**

Feynman's prescription assigns a complex number to each diagram, let us write these as $A$ and $B$. (The values of $A$ and $B$ depend on the momenta and energy of the particles.) The probability of a given scattering occurring is given by $|A+B|^2$. 
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There is no way to say which of the two underlying processes represented by the two diagrams actually occurred. Furthermore, we cannot even say there is a probability of each process and then add the probabilities, since \(|A+B|^2\) is not the same number as \(|A|^2 + |B|^2\).

For example, let consider \(A = 5\) and \(B = -3\). Then we might think the probability of the process represented by \(A\) was \(|A|^2 = 25\), while that represented by \(|B|^2 = 9\). Given this, we would be tempted to assign the probability \(34\) to having either the \(A\) or the \(B\) process occur -- but the quantum answer is \(|A+B|^2 = 22 = 4\). That is, the two processes interfere with one another and both contribute to make the net result smaller than it would be if either one alone were the only way to achieve the process!

This is the nature of quantum theories -- unobserved intermediate stages of a process cannot be treated by the ordinary rules of everyday experience.

In both diagrams, the photons that appear at intermediate stages are virtual particles that are not observable.

Scattering

"Scattering" is a physics term for what happens in a collision – both particles change direction, they exchange some momentum and some energy in the process.
<table>
<thead>
<tr>
<th>Name of Process Description</th>
<th>Feynman Diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compton scattering</td>
<td><img src="image" alt="Compton scattering" /></td>
</tr>
<tr>
<td>electron + photon</td>
<td><img src="image" alt="electron + photon" /></td>
</tr>
<tr>
<td>electron + photon</td>
<td><img src="image" alt="electron + photon" /></td>
</tr>
<tr>
<td>Bremsstrahlung</td>
<td><img src="image" alt="Bremsstrahlung" /></td>
</tr>
<tr>
<td>electron in medium</td>
<td><img src="image" alt="electron in medium" /></td>
</tr>
<tr>
<td>electron + photon</td>
<td><img src="image" alt="electron + photon" /></td>
</tr>
<tr>
<td>Møller scattering</td>
<td><img src="image" alt="Møller scattering" /></td>
</tr>
<tr>
<td>electron + electron</td>
<td><img src="image" alt="electron + electron" /></td>
</tr>
<tr>
<td>electron + electron</td>
<td><img src="image" alt="electron + electron" /></td>
</tr>
<tr>
<td>Pair production</td>
<td><img src="image" alt="Pair production" /></td>
</tr>
<tr>
<td>photon + photon</td>
<td><img src="image" alt="photon + photon" /></td>
</tr>
<tr>
<td>electron + positron</td>
<td><img src="image" alt="electron + positron" /></td>
</tr>
<tr>
<td>Pair annihilation</td>
<td><img src="image" alt="Pair annihilation" /></td>
</tr>
<tr>
<td>electron + positron</td>
<td><img src="image" alt="electron + positron" /></td>
</tr>
<tr>
<td>photon + photon</td>
<td><img src="image" alt="photon + photon" /></td>
</tr>
<tr>
<td>Bhabha scattering</td>
<td><img src="image" alt="Bhabha scattering" /></td>
</tr>
<tr>
<td>electron + positron</td>
<td><img src="image" alt="electron + positron" /></td>
</tr>
<tr>
<td>electron + positron</td>
<td><img src="image" alt="electron + positron" /></td>
</tr>
<tr>
<td>or</td>
<td><img src="image" alt="or" /></td>
</tr>
</tbody>
</table>
A note on conservation of energy and momentum.

• Every actual physical process must respect these laws!
• Every initial and final particle must either be real or come from the matter.
• EGS pictures show only real particles.

You can draw Feynman diagrams that look perfectly reasonable but do not represent possible processes because they are forbidden by conservation of energy or momentum rules.

For example, an isolated single real photon no matter how much energy it has, cannot produce an electron-positron pair that obey these laws. Similarly pair annihilation in vacuum cannot produce just one real photon.

3.) Sample of EGS Images
Introduction

**Photon Interaction Lab**

Photons interact with material in many ways, but the three most dominant mechanisms for energies above a few keV are:

**Photoelectric Effect**

The photon's energy is totally absorbed by the atom and an inner-shell electron is ejected. Immediately following this, an outer shell electron makes a transition to fill the gap in the inner shell and in the process emits photons (X-rays).

**Compton Scattering**

The photon scatters off an electron in an outer orbit of an atom and the energy of the incident photon is then shared between the outgoing electron and the scattered photon.

**Pair Production**

The photon "materializes" into an electron and its antiparticle, a positive electron (a positron), while in the presence of the electromagnetic field of the nucleus.

The above three mechanisms account for more than 99% of the interactions that take place between photons and matter. Which of the interactions is the most important at any given time depends on the energy of the photon and the medium in which it is traveling.

However, these interactions are quantum in nature. This means that a specific interaction is never guaranteed, it is simply more (or less) probable than the others (depending on energy and material). The EGS program simulates this quantum nature by randomly selecting which interaction, if any, occurs with the correct (average) probabilities.

In the following exercises, you will learn how to recognize these three basic interactions using the EGS computer code, which we have set up to allow you to create visual images of particle tracks in color. In particular, you will learn about:

- Interaction distances (the average distance to a collision).
• Which interaction type dominates.
• The random, but statistically determined, behavior of nature.

**Interactions of 0.3 MeV photons in aluminum and lead**

Figures 1 through 3 are provided for you so that you can predict how photons will interact with matter in an average sort of way. The EGS code will then allow you to visualize these events in a statistical sense, and you judge whether or not things look like what you predict.

In this first exercise we will guide you through the use of the three figures by filling in some tables for you. However, you will run the EGS code. In Exercise 2, we will increase the energy of the photon to 10 MeV and let you do all the work!

We have purposely chosen two types of materials for this study, one with a low atomic number (Al, Z=13, r=2.70 g/cm³), and one with a high atomic number (Pb, Z=82, r=11.3 g/cm³), so that you can predict beforehand and visualize afterwards how the choice of medium affects interactions.
Using Figure 1, we have determined the average distance, \( l \) (cm), that a 0.3 MeV photon is expected to travel before interacting in either aluminum or lead, and we have put our numbers in the table below.

<table>
<thead>
<tr>
<th></th>
<th>Al (cm)</th>
<th>Pb (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( l )</td>
<td>3.6</td>
<td>0.23</td>
</tr>
<tr>
<td>( P_{int} )</td>
<td>0.43</td>
<td>1.0</td>
</tr>
</tbody>
</table>

What this tells us is that on average a 0.3 MeV photon will travel 3.6 cm in aluminum before experiencing an interaction, but it will travel about 0.23 cm for this to happen in lead.

Let’s now choose a thickness for the slabs of material, which we will soon have EGS throw photons at. From Table 1, a good guess might be to pick an aluminum thickness of 2 cm, because with a \( l \) of 3.6 cm, we can anticipate that some of the photons might pass right through the slab without interacting at all. On the other hand, the \( l \) for lead is 0.23 cm, suggesting just the opposite—most of the photons impinging upon the lead will probably interact with it.

Fortunately, we have a simple formula for also determining the probability that a photon will interact as it passes through a slab of material:

\[
P_{int} = 1 - e^{-t/\lambda} = \text{probability to interact}
\]

In this equation \( t \) (cm) is the thickness of the slab and \( l \) comes from Table 1. As you may have guessed, the second row in our table contains values for \( P_{int} \), obtained by using this formula (try it yourself). So what does it tell us? Well, we should expect that about 43% \( (P_{int} = 0.43) \) of the time the incident photons will interact within 2 cm of aluminum, which means that 57% of them will pass on through without doing anything.

On the other hand, 2 cm of lead seems to be a "show stopper" (pun intended), for the prediction is that 100% \( (P_{int} = 1.0) \) of the time they will interact. But remember, life in the atomic world is based on probabilities, and you can bet that if we throw enough photons at the lead slab, even one that is this thick, a few will occasionally get through. This is a statistical world that we live in and the best we can do is to make predictions about what will happen on average. EGS is designed to demonstrate this for us.
Now, before moving on to the EGS "experiment" that we are going to ask you to perform, we need to gather a little more information. As we have been saying, nature not only randomly decides when a photon is going to interact with matter, it also chooses the type of interaction in a random way. The actual physics itself is based on part of the standard model known as quantum electrodynamics (QED), and with it we can make plots like those provided to you in Figure 2 and Figure 3. The curves in these figures provide us with a way of determining the relative probability—e.g., a fraction that lies between 0 and 1—that an interaction, once it occurs, will be one of the three basic mechanisms that we are studying.

Again, remember that if there is a 60% chance that a particular interaction occurs, there is a 40% chance that something else could happen. Both cannot happen at the same time. Nature spins its random numbers, and the simulation does the same. So let’s continue with our exercise by making use of the two new figures we have provided you.

For the 0.3 MeV photon, we have determined the relative probability (contribution) for each of the three processes for both aluminum and lead, and we have entered this information into Table 2 shown below (note that we are talking about "relative" probabilities and their sum must add up to unity).
Table 1 told us that in a 2 cm slab of aluminum we can expect 43% of the photons to interact. Table 2 tells us to expect that 100% of the time interactions will be of the Compton variety (photon scatters off an orbital electron of an atom and the two particles share the incoming energy as they make their way through the rest of the material). Let's have the EGS code demonstrate this for us before we go any further.

In the fields on the "EGS to Order" Simulation Tool (this link will open the tool in a new browser window) change the following parameters from their default settings.
Then you only need to click on the "generate" button and, voila, you get what you see. You can keep clicking the generate button and each time you get a different picture with the same average probabilities... just like nature does it.

What about switching the slab from 2 cm of aluminum to 2 cm of lead? Well, just do it!

**Interactions of 10 MeV photons in aluminum and lead**

In this exercise we have simply increased the photon energy from 0.3 MeV to 10 MeV and we would like you to fill in all the blanks in a new set of tables that we have provided for you (below). Simply use Figures 1 through 3, like we did in the previous exercise, to complete the tables.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle Type</td>
<td>Photon</td>
</tr>
<tr>
<td>Incident Kinetic Energy</td>
<td>0.3 MeV</td>
</tr>
<tr>
<td>Number of particles in beam</td>
<td>10</td>
</tr>
<tr>
<td>Incident particle vertical spread Uniform in Y axis</td>
<td>On</td>
</tr>
<tr>
<td>Target Medium</td>
<td>Lead</td>
</tr>
<tr>
<td>Target Length</td>
<td>2 cm</td>
</tr>
<tr>
<td>Target Radius</td>
<td>1 cm</td>
</tr>
</tbody>
</table>

Then you only need to click on the "generate" button and, voila, you get what you see. You can keep clicking the generate button and each time you get a different picture with the same average probabilities... just like nature does it.

What about switching the slab from 2 cm of aluminum to 2 cm of lead? Well, just do it!

### Interactions of 10 MeV photons in aluminum and lead

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>λ (cm)</td>
<td></td>
</tr>
<tr>
<td>P_{int}</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Particle Type</th>
<th>Compton</th>
<th>Pair Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photoelectric</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al</td>
<td>0.00</td>
<td>100.00</td>
</tr>
<tr>
<td>Pb</td>
<td>0.78</td>
<td>0.22</td>
</tr>
</tbody>
</table>

*Engineering Aspects of Food Irradiation*
When you have filled in the blanks, use the "EGS to Order" simulation tool to create the images and see if the images match your predictions. This time we recommend that you select an aluminum thickness of 20 cm and a lead thickness of 3 cm. Why? For no special reason other than it will make the tracks in the EGS images a little easier to discern from one another (wait and you will see what we mean). Also, always choose the radius to be half of the thickness because this gives us a nice aspect ratio for the picture. And, make sure your tracks are "spread out" in the Y axis so you can distinguish them.

Treating Cancer with radiation

Now that you have learned about EGS, let's see one way EGS has been used in a "real world" application...to improve radiation cancer treatments.

Medical Problem

Approximately one in eight people receives radiation treatment for cancer. Electron accelerators produce the x-rays used in these treatments. The first accelerator for medical use was built at Stanford in 1956. Today every major hospital has one of them.

A medical physicist needs a computer program to calculate radiation effects in the body and plan treatments. The problem is how to give maximum radiation dose to the tumor with minimum damage to healthy tissue.

The EGS Software Solves the Medical Problem

The "Electron-Gamma-Shower" (EGS) is now the most accurate method available to calculate radiation effects in body tissue and determine dosages. SLAC physicists originally developed the EGS program to model the passage of radiation through particle detectors. It has been "tuned" to match a wide variety of measured effects, adapted in collaboration with the National Research Council of Canada.

EGS uses the density and the locations of various tissue types in each patient's body in its calculations. Most body tissue has about the same density as water, but bones
are twice as dense and lung tissue 1,000 times less dense. A model that treats all tissues alike would not do the job!

The EGS program is used as the "gold standard" to check whether simpler, faster, approximate calculation methods that are used by practitioners are doing the job accurately enough. As treatment techniques improve, more accurate calculations are needed.

**The physician wants to maximize radiation dose to the tumor and, at the same time, minimize radiation damage to the patient's healthy tissue.**

Consider these facts:

- radiation has been used quite successfully for many years to treat cancer. . . this is called radiotherapy.
- barring a miracle cure, roughly one in eight of us in our lifetime will find ourselves being treated for cancer using radiotherapy.
- almost all radiation treatments involve electrons or photons (also called x-rays).
- maximizing dose to the tumor while minimizing dose to healthy tissue is the goal of efficient radiotherapy.

Patient dosimetry is the accurate determination of the radiation dose given during radiotherapy. The equipment used today to perform radiotherapy, such as the electron electron accelerator, is complex. The actual radiation dose to the patient and to the tumor is dependent upon the radiation scattering from components inside the machine as well as structures within the human body.

Consider a cross section of the human body as shown in the diagram on the right. The organs in the body can be viewed as discrete units, each with boundaries and densities. Most tissue in the body has a density close to water. However, the lungs are filled with air and, as such, are 1,000 times less dense than surrounding tissue. The bones, on the other hand, are almost twice as dense as the surrounding tissue. These differences in densities are what we call "discontinuities" and they make the dosimetry problem very complex, as you might expect, particularly near the "interface"

**Why is radiation an effective treatment for some types of cancers?**

To explain this concept, the following is an excerpt from:
Introduction


Cell Radiosensitivity Theories

Ideally we would like to have a law analogous to Newton's Laws of Motion or Ohm's Law which would predict exactly the kind and amount of injury produced in a given cell following an exposure to radiation. Unfortunately, such a law remains yet to be discovered. The field of radiobiology is thus dependent on "rules of thumb" to estimate radiation effects. Simplistically, this is the underlying reason for the adoption of the ALARA philosophy. ALARA is the acronym for "As Low As Reasonable Achievable." This attitude is applied to radiation doses received by nuclear technicians because we have no accurate theory to predict what really happens at the low dose rates of 0.01 to 0.05 Sv (1 to 5 rem) per year encountered occupationally.

The oldest, and perhaps best, rule of thumb was developed by two French radiobiologists, Bergonie and Tribondeau, in 1906. It offers a prediction about the relative sensitivity of two different types of cells or tissues to radiation. The so-called Law of Bergonie and Tribondeau concluded that cells tend to be radiosensitive if they have three properties:

4. Cells have a high division rate.
5. Cells have a long dividing future.
6. Cells are of an unspecialized type.

The first condition can be determined by measuring the cell cycle time, i.e., the time between divisions. The second property refers to the fact that many cells go through phases in an overall life cycle. They begin by undergoing many cell divisions (childhood). They then enter a phase in which they stop active division and instead put together the internal structures to function in some usable capacity (adolescence). Finally they enter the last phase where they function fully in the job assigned (adulthood). Cells with a long dividing future would be those in the early immature phases where they are still dividing.

The last criterion, unspecialized, needs further comment. In the biological sense, this means a cell which is capable of specialization, at some future time, into one of several different "adult" cell types. An example might be one of the immature blood cells. Many types of blood cells are "born" unspecialized. Depending on the feedback signal received long after they are formed, they can choose to "grow up" and mature into lymphocytes, or different types of granulocytes. Probably the most
unspecialized human cells is a fertilized ovum. From the single cell, daughter cells develop into such widely different mature cells as bone, brain, blood, and finger-nails.

The generalization of the Law of Bergonie and Tribondeau is that tissues which are young and rapidly growing are most likely radiosensitive. A very practical application of the Law is given by NRC Regulatory Guide 8.13 which is titled "Instruction Concerning Prenatal Radiation Exposure." This Guide requires that woman of reproductive age be informed of the increased risk of injury of the human fetus from radiation exposure because such a tissue meets all the criteria of the Law of Bergonie and Tribondeau. The human fetus is particularly sensitive in the first few weeks of pregnancy when organs are forming. This is the time period when the woman may not be aware of her pregnancy. Most radiation protection standards recommend that the dose to a developing embryo and fetus be kept below 0.5 rem during the entire nine months of gestation.

Another rule of thumb is the Target Theory. It was developed in the 1920s and assumed that cells had a single, absolutely essential-to-life key structure (the target) which determined if a given cell survived or died after radiation exposure. If the target were hit, the cell would die -- a miss meant survival. Unfortunately, later work showed that animal cells don't have such a target. The theory applies strictly only to certain yeasts and viruses.

A final theory of radiosensitivity is worth mentioning. This is the ICV Theory developed by Sparrow at Brookhaven National Lab in 1965. It is able to accurately predict the lethal dose of radiation to any type of plant based on knowledge of the size of the nucleus and the number of chromosomes. Unfortunately it fails miserably when applied to animal or human tissues.

The Physics Problem

The medical physicist wants to create radiation and to know how it transports through the body so the physician can use the radiation for radiotherapy.

In the early days of SLAC, scientists had the job of determining the amount of shield material necessary to protect people and equipment from radiation generated during experiments. These scientists used physics knowledge and mathematical tools to solve these shielding problems. This field of study became known as radiation transport because the particles of radiation bounced around within the shield -- i.e., they were "transported
Introduction

When high-energy radiation in the form of electrons and photons hit matter, they travel randomly (or "walk") through the material, interacting with matter in various ways that are predicted by the laws of physics. The graphic above shows a computer simulation example of an interaction of an electron (blue) during a transport process. Such interactions can, in turn, generate more electrons and photons, producing a multiplying effect known as a shower (shown below).

Although the physics involved in each individual interaction in the transport process is well understood, the randomness of the individual interactions and the mul-
tiplying effect during a shower makes calculating the outcome extraordinarily difficult. EGS was developed to solve this mathematical physics problem.

**EGS and the Human Body**

Medical physics is a very diverse field that applies the knowledge gained in other areas of physics (such as the physics at SLAC) and applies the knowledge to better understand illness and heal people. CAT scans, mammography, and other x-ray imaging techniques have been developed by physicists working in medicine, and the EGS computer code has become an important tool in optimizing these techniques.

The experiment described below shows how accurately EGS can model features within the human body. This is an excerpt from the article entitled "EGS, A Technology Spinoff to Medicine" from the Beam Line, Spring 1991 issue.

Using a 20-MeV accelerator, scientists at the National Research Council of Canada (NRCC) placed small cylinders of aluminum and air within a large tank of water and irradiated them with electrons (see picture below).

Measurements were made at various locations in the water, particularly near the surface of the cylinder, and computer simulations were performed using EGS. In the results presented in the figures below, the smooth curves represent the measured data and the histograms are EGS calculations.
A typical depth-dose curve in a homogenous "phantom" of water -- i.e., containing no voids or solid materials -- is shown in the figure at right. The other two curves demonstrate how an aluminum cylinder attenuates, and an air cylinder enhances, the dose along the central axis within the phantom.
The radial dose profile at various locations downbeam from the air cylinder was also measured and the results are shown in the final set of figures at right. Clearly the dose perturbations caused by discontinuities are well predicted by EGS, lending considerable confidence to the ability of the program to simulate the passage of electrons through the human body.