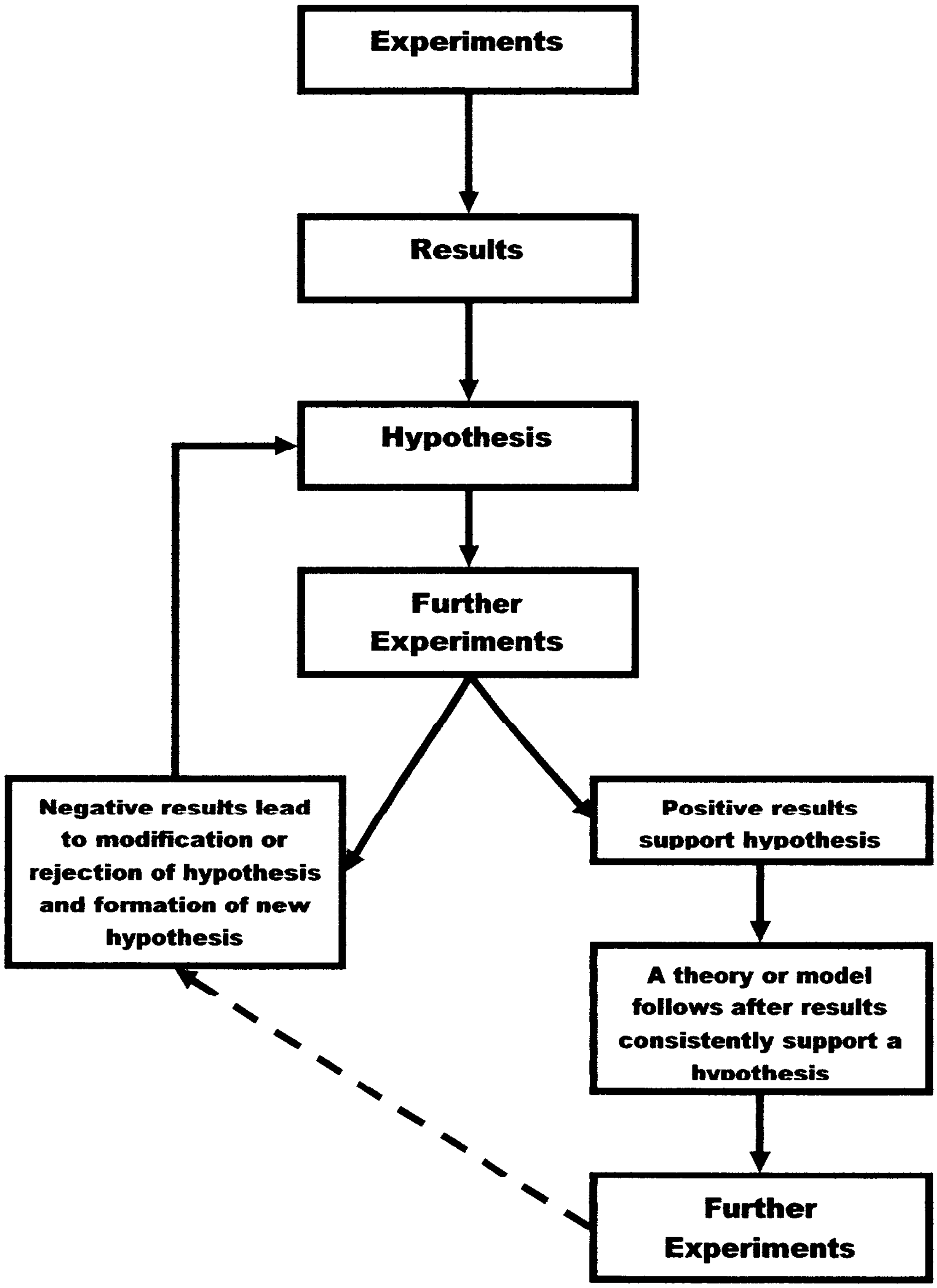
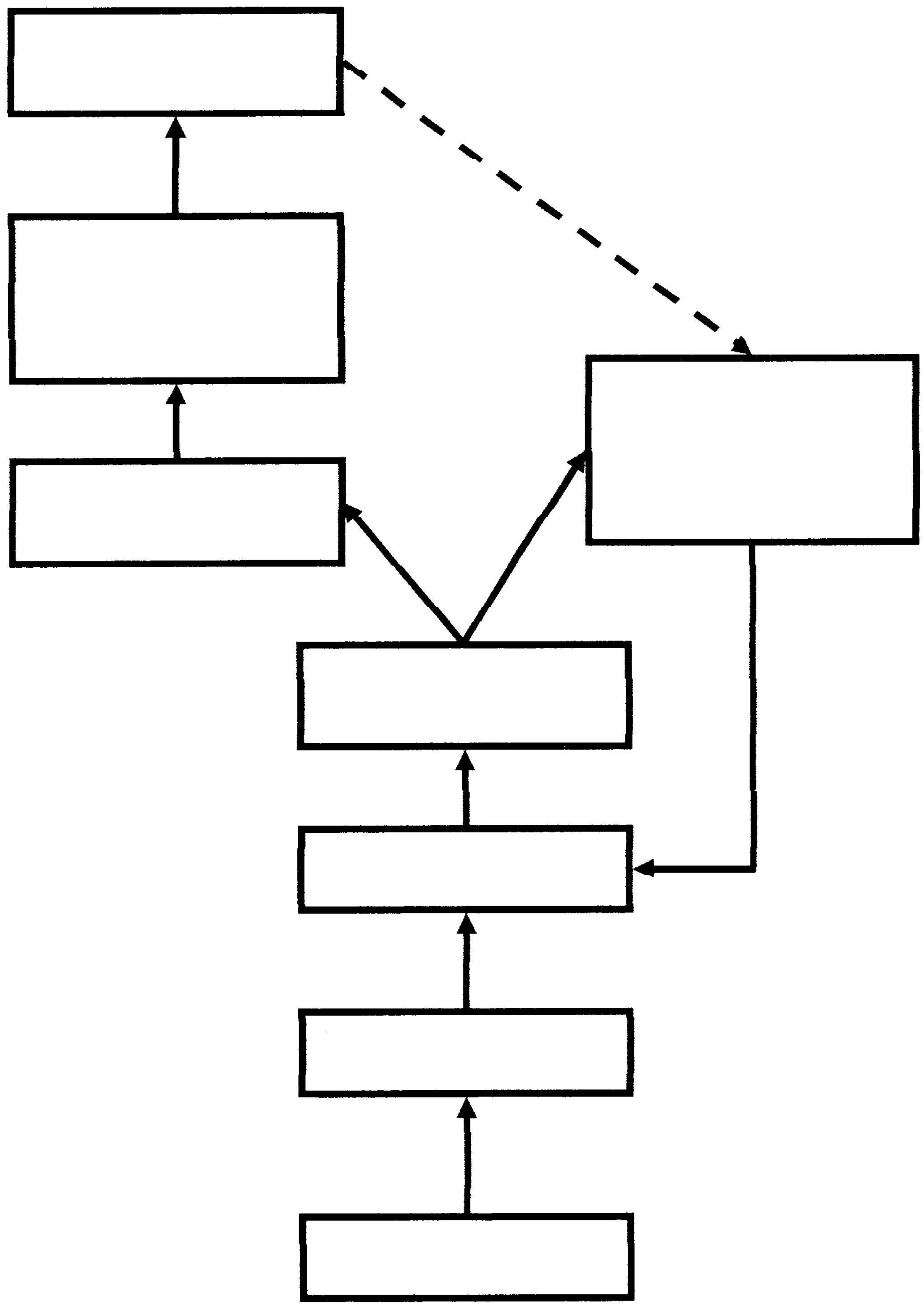

Experiments
Results
Hypothesis
Further Experiments
Negative results lead to modification or rejection of hypothesis and formation of new hypothesis
Positive results support hypothesis
A theory or model follows after results consistently support a hypothesis
Further Experiments

QN06-1



QN06-2

Teacher Information for Polar Bear Research Project

Objective:
To give students the opportunity to use the scientific method

Materials:
Several sets of 5 dice
Handouts on which to record hypotheses and data

Time Required:
This activity takes between 15-45 minutes depending on the depth and details of the discussion

Procedure:

1. Give the students the initial information that "Polar Bears come in pairs and they sit around a whole in the ice.
2. Throw the dice and tell the students how many polar bears. (This is the first experiment)
3. Ask students to record results and propose a hypothesis. Have students test the hypothesis.
4. When a student thinks they have the correct model for the results have them demonstrate proficiency by giving the correct answer three times in a row.
5. When they have demonstrated proficiency give them 5 die and let them direct their own research group.
6. After a while when students are becoming frustrated ask them to propose a way to modify the experiment to improve the results so more information could be obtained. (They will propose throwing fewer dice etc.)
7. Perform the modified experiment.

Possible Discussion Points:

1. I use this as an opportunity to discuss the importance of documenting their process and results.
2. Students may require instruction on how to propose a hypothesis
3. When the students are proposing modifications the opportunity to discuss numbers of variables and how to control them may arise.
4. Many students will become frustrated. This is a good time to discuss that failures in science sometimes provide important information.

Extensions:
1. Have students read a scientific study and place the components of the study into the framework of the scientific method.
2. Depending on the discipline consider proposing a few simple problems for students to design experiments to solve.

QV 06-7

Polar Bear Research Project

Background information:

1. Polar bears com in pairs
2. They sit around a whole in the ice

Hypothesis
1____Result________

Hypothesis
2____Result________

Hypothesis
3____Result________

Hypothesis
4____Result________

Hypothesis
5____Result________

Hypothesis
6____Result________

Hypothesis
7____Result________

QN06-4

Hypothesis
8____Result_____

Hypothesis
9____Result_____

Hypothesis
10____Result_____

Hypothesis
11____Result_____

Hypothesis
12____Result_____

Hypothesis
13____Result_____

Hypothesis
14____Result_____

Hypothesis
15____Result_____

QN06-5

Eleusis

The game of predictions

1 Equipment

- A deck of playing cards,
- Scoring sheets,
- a keen intellect.

2 Introduction

Part of studying science is learning **induction,** the art of reasoning from specific observations to general laws. Induction can be a complicated business, and even modern logicians argue about it. In this lab you will try a simple investigation of inductive reasoning by playing a card game called *Eleusis.* *

In most card games you know the rules which determine what cards can and cannot be played. In the game of Eleusis you are trying to determine the rules themselves!

3 The Meta-Rules

Eleusis is played by 4—7 people, with a deck of standard cards. (If you have more than four people you may need a second deck.) At the beginning of each hand, one person is designated the **Rulemaker,** and everyone else is referred to simply as a "player". The role of Rulemaker rotates from hand to hand. A game consists of a set of hands where everyone has played the role of Rulemaker once.

The Rulemaker decides upon a *rule* for the hand and secretly records it on a piece of paper. The rule must decide whether a card played by a player is right or wrong based on any of the following properties:

1. the card's suit (or color),
2. the card's value,
3. the card's position in the sequence (in relation to previously laid correct cards' suit or value).

The Jack, Queen and King are counted as 11, 12 and 13, respectively. Also, a rule must cover all possibilities: any card laid down must be considered either right or wrong. A few examples of rules:

- Only even cards (counting the queen as even) are correct.
- The number of the card played must be one more or one less than the last correct card.
- The colors must alternate. (If the 2♣ was first laid down, the next card would be correct if it were a diamond or a heart, and incorrect if it were another club or spade.)

---

*This is a simplified version of the game. See section 6 below for references to the full rules.

QN06-6

The rule *cannot* depend on who laid the card, how he laid it, which deck the card came from, whether the card is aesthetically pleasing at the moment or not, etc. Only the suit, value, and position in the sequence determine its rightness or wrongness.

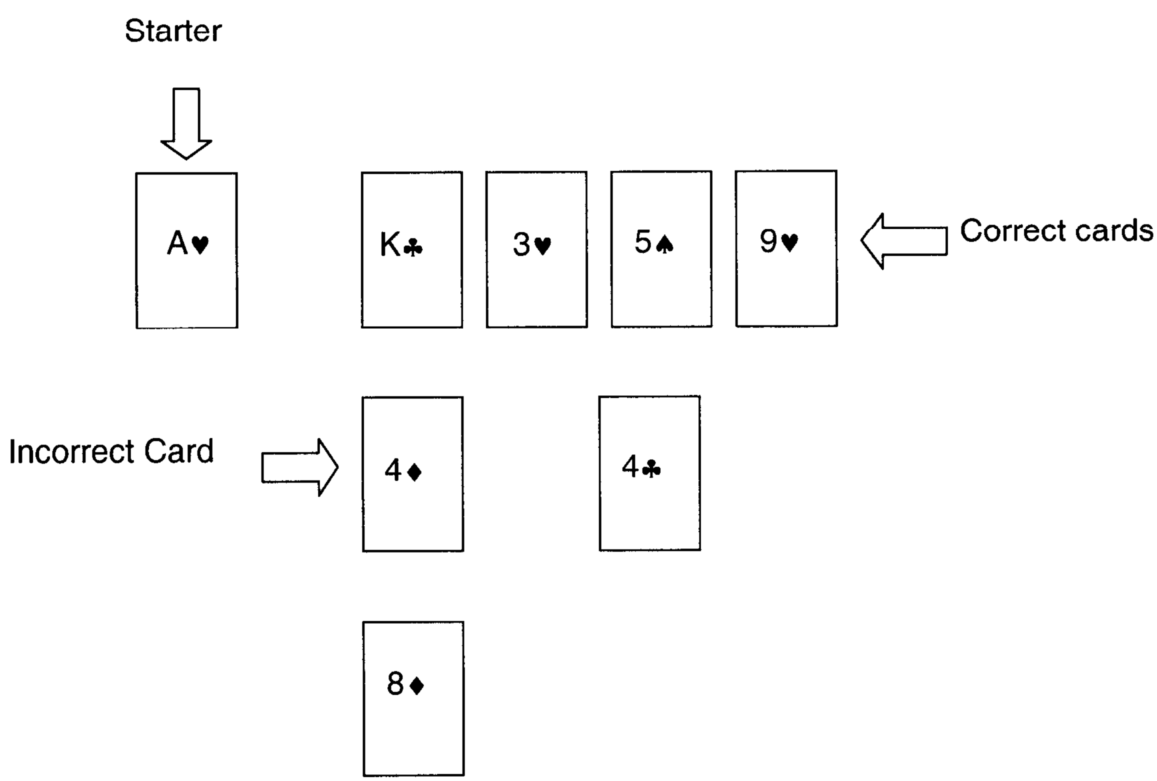
It is very easy to come up with more complicated rules. For example:

- If the last correct card is red, play an even number. If the last correct card is black, play an odd number.
- The cards must be the digits of π, starting after the decimal (ace four ace five ...).
- The correct card equals the square root of the sum of the previous cards evaluated modulo 13.

These rules, while legal. will result in a low score for the Rulemaker (as will be explained below), as well as frustrated and annoyed players. Thus it is in the Rulemaker's best interest to choose simple rules. *It is strongly recommended that you stick to simpler rules in the beginning.*

The Rulemaker places a single starter card down that obeys the rule. He or she then deals out twelve cards to each of the other players. (You may need more than one deck). Play proceeds clockwise from the Rulemaker. The player lays down a card which s/he thinks is correct. (This card is like a small "experiment" to test the rule.) After the card is laid down, the Rulemaker says whether the card was right or wrong. If the card is right, it is played in a horizontal line with the starter card, and the player wins a point. If the card is wrong, the card is placed vertically below the last correctly played card. The rulemaker does not play any cards after placing the starter: he or she simply states if the *other* cards played are correct or incorrect. The game ends after 10 such rounds.

Below is a sample of a game. The Rulemaker used the *A* ♥ as a starter. The first player tried the K♣, which was correct. The next player tried the 4♦, which was incorrect, and placed below the line of correct cards. The third tried the 8♦, which was also incorrect. The fourth tried the 3♥ which was correct, and placed in line with the correct cards.



QNOC-7

Can you guess the rule that generated the above sequence of cards? It is given at the bottom of the page. (Try before looking!) *

It may arise that the player thinks that they have no card in their hand which they can play. In this case they declare this as their "play". The Rulemaker then looks at their hand. If the player is correct, they score a single point, discard their entire hand and place it below the last correct card, and draw a new hand with one fewer cards. If the player is incorrect, the Rulemaker selects from their hand a playable card, and adds it to the string of correct cards. The player has two points *subtracted* from their score as a penalty.

You may have realized that one of the goals of the game is for the players to figure out the rule. Once someone thinks they have done that, they may declare discovery. You can declare discovery at any time, regardless of whose turn it is. You do not have to state your rule when declaring discovery. The discoverer is given the honorary title of the **Landau.**** A marker (such as a coin) is put on the card where the discovery was declared, and the Landau puts down his cards; they will not be used again this hand. Only one player can be Landau at a time.

The game continues as before, except that the Landau says whether a card is right or not, and the Rulemaker says whether the Landau is right or not. So long as the Landau is right, the game continues; but when the Landau is wrong, he or she is demoted to the status of **Lab Rat.** The card on which the player fell from grace is marked, and the discredited player waits until everyone else is done with the hand. As soon as one Landau is deposed, another player may declare discovery. If all the players are turned into Lab Rats, the hand is over.

Play continues until the players are out of cards. The Rulemaker then reveals the rule. The scores are computed from the scoresheet, with the added rules below.

It is best to keep a running score on the tally sheets provided. As each player places a card, the player (and the Landau, if there is one) is given the appropriate score.

Normal players score one point for every correctly played card or declared "no play".

The Landau scores one point for every correct card before announcing discovery, and one point for every correct ruling after their discovery.

Lab Rats score as The Landau up until their discovery is proved fraudulent. A penalty of 5 points is subtracted from this total due to the besmirching of their reputation.

The Rulemaker scores twice the *difference* between the highest and lowest scores of the other players. Thus it the Rulemaker does well when at least one player determines the rule and at least one other player does not.

Below is an example of a section of a scoresheet from a game played by Abigail, Berthold, Carruthers, Dillsworth, and Elspeth, or **A, B, C, D** and **E**. **A** is the rulemaker for this hand. She writes down the rule, and places the A♥ as the starter card.

---

*The rule is: "Alternating red and black cards, all odd".

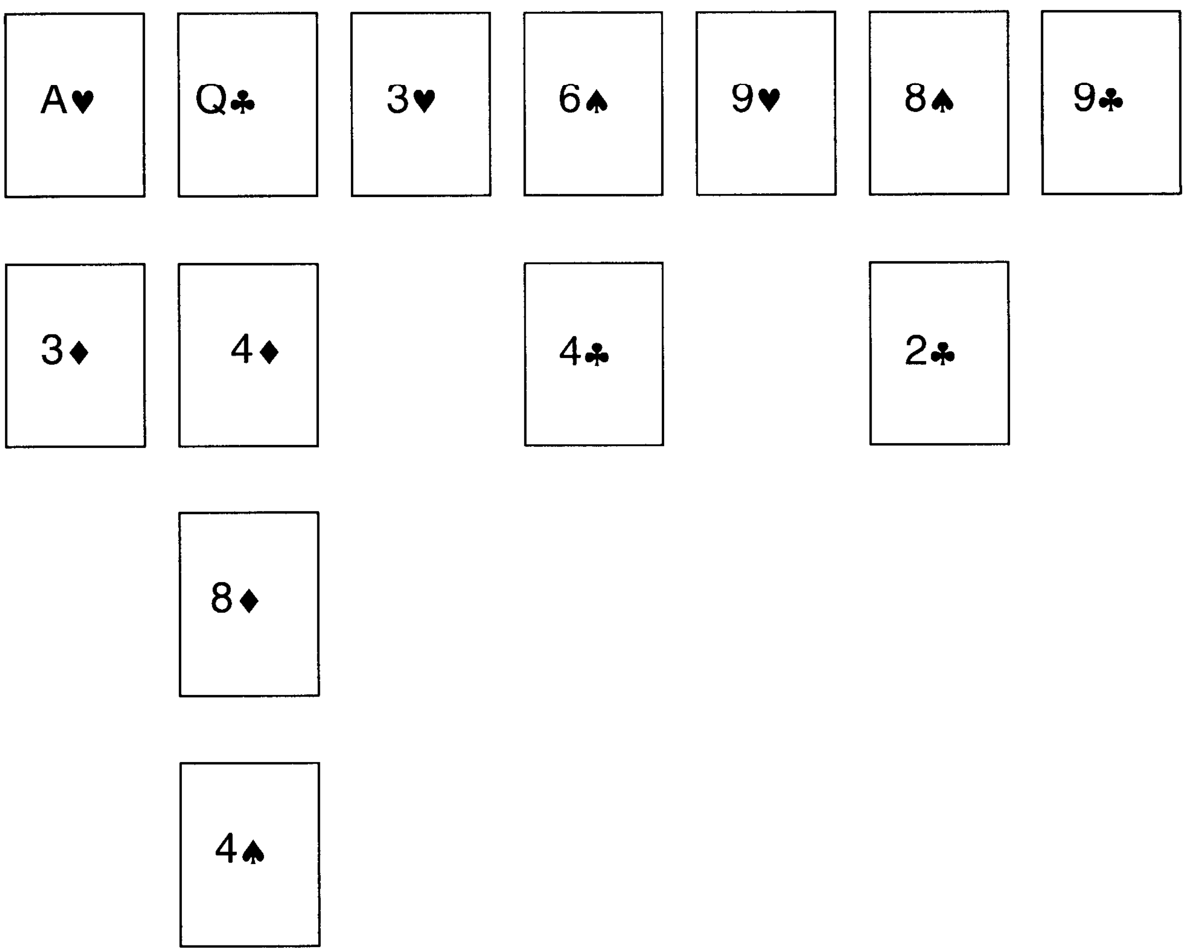
**The title is named after Lev Davidovich Landau, one of the most brilliant physicists of the 20th century. Landau was famous for his annoying habit of making brief, elegant arguments that were always correct.

On the first turn **B** guesses the 3♦, which is wrong. **C** guesses the Q♣ which is correct. **D** guesses the 4♦, and **E** guesses the 8♦ which are both wrong.

On the second turn poor **B** guesses the **4♠** which is wrong. **C** guesses 3♥ and is correct. **D** guesses the 6♠ and is also correct. **E** guesses the **4♣** and is wrong.

On the third turn, **B** plays the 9♥ and is correct. Boldly he states that he has discovered the rule. He now sets down his cards, and does not play them for the rest of the hand. **C** plays the **8♠** and **B** claims this is correct. **A** agrees, so *both* **B** and **C** get a point. Next, **D** plays a **2♣**, which **B** claims is incorrect. **A** agrees and **B** gets one point. Finally, **E** plays **9♣**, which **B** claims is incorrect. **A** says this is wrong, and **B** is demoted to the status of "lab rat". **E** gets the point for her correct play.

Name	**Abigail**	**Berthold**	**Carruthers**	**Dillsworth**	**Elspeth**
Turn 1		**0**	**1**	**0**	**0**
Turn 2		**0**	**1**	**1**	**0**
Turn 3		**1+1+1-5**	**1**	**0**	**1**



4 Procedure

Split up into teams of 4-6 players. Play enough hands so that every player has been rulemaker at least once.

In the last half-hour of class, the laboratory TA will act as the rulemaker, and each team will cooperate as a single player. Play as many hands as time allows, rotating which team guesses first. The highest scoring team by the end of class will not have to turn in written answers to the questions below. Everyone else in the lab will have to write up answers and turn them in by the start of the next lab.

5 Questions

Answer the following essay questions in complete sentences. It will take at least four sentences for each question. Your answers must be neat and legible. Incomprehensible, messy or fragmentary answers will receive little or no credit.

1. Did you ever discover a rule simpler than the Rulemaker's, and was it very often right? Does this ever happen in scientific research? Give an example.

2. Why are the time of day, the gender of the player, the room temperature or the mood of the Rulemaker not good quantities to be considered in writing rules? Write at length and in detail on how this relates to tests of physical laws.

3. Give at least three ways in which the game of Eleusis is a model that resembles scientific research. Give at least three ways is which it fails to model research.

4. One of the fundamental assumptions in Eleusis is: *there is a rule that determines if a card is correct or not.* What is the corresponding assumption in scientific research? How justifiable is this assumption?

6 Supplemental Information

Eleusis can be found in the June 1959 issue of Scientific American in the "Mathematical Games" department by Martin Gardner. An updated version appeared in the October 1977 issue in the same department. You can also find it in a chapter of *Abbott's New Card Games* by Robert Abbott, and in a book titled *New Rules for Old Games* by the same author.

Other versions of the game call for players to pick up a card when they are incorrect; the game continues until one player uses up all of their own cards. In this version you can also play a run of several cards at once, with a large penalty if you are incorrect. These versions tend to take much longer to play. However, you are encouraged to experiment with the meta-rules. After all – experimenting with rules is the whole point of this particular lab!

QN06-9

Score Sheet

Name					
Turn 1					
Turn 2					
Turn 3					
Turn 4					
Turn 5					
Turn 6					
Turn 7					
Turn 8					
Turn 9					
Turn 10					
Total					

QN06-10

Initial Workshop Survey

State whether you agree of disagree with each of the following statements

1. There are subatomic particles that have no mass and no electric charge
2. Some particles can travel through billions of miles of matter without being stopped (interacting)
3. Antimatter is science fiction NOT science fact.
4. Particle accelerators are used for cancer treatment
5. The smallest components of the nucleus of an atom are protons and electrons.
6. Particles and antiparticles can materialize out of energy
7. Particle physicists need larger accelerators to investigate larger objects
8. Magnets are used in circular accelerators to make the particles move faster.
9. Work done by particle accelerators is helping us understand the very early development of the universe.
10. Gravity is the strongest of the fundamental forces in nature
11. There are at least one hundred different subatomic particles.
12. All matter is made of leptons and quarks
13. All of the particles needed to formulate a complete model of the universe have been discovered
14. Friction is one of the fundamental forces of nature
15. Students who are in high school now will make major contributions to accelerators currently being built and planned.

The Goal of this survey is to stimulate discussion and curiosity about particles.

QN06-11

Atomic Target Practice
Rutherford Scattering and the Nuclear Atom

Introduction:

The Rutherford gold foil experiment is one of the most famous of all time. More than 25 years after conducting the experiment, Ernest Rutherford described the results this way:

"It was about as credible as if you had fired a 15-inch shell at a piece of tissue paper and it came back and hit you."

The experiment itself was actually the culmination of a series of experiments, carried out over a five-year period, dealing with the scattering of high-energy alpha particles by various substances.

Ernest Rutherford received the Nobel Prize in Chemistry in 1908 for his investigation into the disintegration of the elements as a result of radioactive decay. Among the products of the radioactive decay of elements are alpha particles—small, positively charged, high-energy particles. In trying to learn more about the nature of alpha particles, Rutherford and his co-workers, Hans Geiger and Ernest Marsden, began studying what happened when a narrow beam of alpha particles was directed at a thin piece of metal foil. Alpha particles are a type of nuclear radiation, traveling at about 1/10 the speed of light. As expect4ed for such high-energy particles, most of the particles penetrated the thin metal foil and were detected on the other side. What was unexpected was that a very few of the alpha particles were actually reflected back toward the source, having been "scattered" or bent due to their encounters with the metal atoms in the foil target. The number of alpha particles that were reflected back depended on the atomic mass of the metal. Gold atoms, having the highest atomic mass of the metals studied, gave the largest amount of so-called "backscattering"

Rutherford's scattering experiments have been described as a "black box" experiment. The properties of the alpha particles, their mass, charge, speed, etc., were at least partially understood. The atoms making up the target, however, presented Rutherford with a kind of black box; the structure of the atom was not known at the time. In order to explain the results of the scattering experiment, Rutherford had to propose a new model of the atoms. A model that explained the results of the data gathered from the experiment. In 1911 Rutherford proposed the following model for the structure of the atom:

- Most of the mass of the atom is concentrated in a very small, dense central area, later called the nucleus, which is about 1/100,000 the diameter of the atom.
  This was proposed as a result of what data:
  ____
  ____
- The rest of the atom is apparently "empty space"

QN06-12

This was proposed as a result of what data

- The central, dense core of the atom is positively charged, with the nuclear charge equal to about one-half the atomic mass.
  This was proposed as a result of what data

Objective:

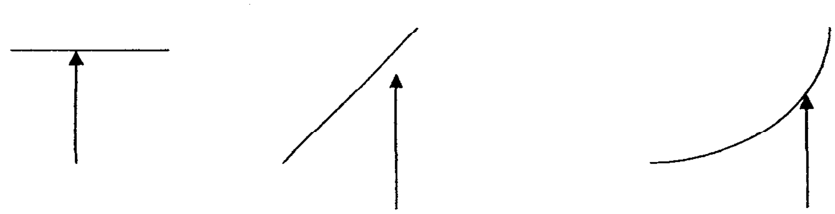
The purpose of this activity is to discover by indirect means the size and shape of an unknown object, which is hidden underneath the middle of a large board. By tracing the path the marble takes after striking the unknowntarget from a variety of angles, it should be possible to estimate the general size and shape of the unknown target.

Pre-Lab Questions

1. Read the material in your textbook about the Rutherford experiment and answer the three questions in the introduction.

2. This activity is a simulation of Rutherford's scattering experiment. Read the entire procedure and compare the components used in this simulation to Rutherford's original discuss what each component in our simulation corresponds to in the original experiment.

3. The key skills in this activity, as in Rutherford's experiment, are the ability to make careful observation and to draw reasonable hypotheses. Assume that the marble strikes following sides of a possible target. Sketch the path the marble might be expected to take in each case.



4. Discuss what information can be inferred if the marble rolls straight through without striking the unknown target.

QN06-13

Materials:

1. foam board with unknown shape attached
2. marbles
3. white paper
4. push pins
5. pencil
6. ruler

Procedure:

1. Form a group of three students
2. Pin the paper to the top of the board (do not look at the shape on the underneath side)
3. Roll the marble with a moderate amount of force under one side of the board. Observe where the marble comes out and trace the approximate path of the marble on the paper.
4. Working from all four sides of the board, continue to roll the marble under the board, making observations and tracing the rebound path for each marble roll. Roll the marble AT LEAST 20 TIMES from each side of the box. Be sure to vary the angles at which the marble is rolled. You may use the rulers as a launching platform.
5. After sketching the apparent path from all sides and angles, the general size and shape of the unknown target should emerge.
6. Form a working hypothesis concerning the structure of the unknown target. Based on this hypothesis, repeat as many "targeted' marble rolls as necessary to confirm or revise the structure.
7. Check your answer with your teacher. DO NOT look under the board.
8. If time permits try an extension, or another shape.

Post Lab Questions

1. Draw the general size and shape of the target to approximate scale in the square below.

GNO6-14

2. The speed of the marble rolls was a uncontrolled variable in this activity. How would the outcome of the scattering test have been different if the marble speed had been faster or slower?

3. Compare the overall size of the target with the size of the marble used to probe its structure. How would the outcome of the scattering test have been different if different size marbles had been used? Explain.

Teacher Notes

Lab Hints

1. Groups of three students seems to work well for this activity
2. this lab can be completed and discussed in 1 50 minute lab period if the students have done the pre-lab assignment before class
3. An extension of the lab is to have the students try different speeds of marbles or different sizes. Students should be cautious about rolling the marbles to fast as loose marbles may cause the teacher to lose their marbles (Ha Ha)
4. I have often wished that I had large flat boxes in which to perform this activity to contain the marbles

Teaching Tips

1. Have students construct a timeline of discoveries in atomic and electron structure. See hand for the time line I have used the past few years.
2. A good source for the timeline research is the Nobel Foundation official web site (www.nobel.se)
3. Although I use this lab as an introduction to the structure of the atom in my chemistry classes, this experiment is also be used as a introduction to a discussion of particle accelerators and can be used to introduce a discussion of particle physics.

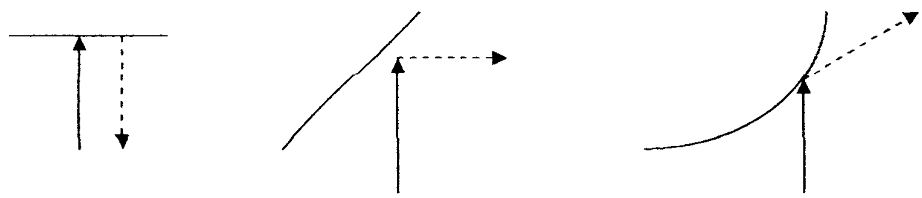
Answers to Questions;

Pre-Lab Questions

1.
   a. The first bullet point was inferred from the fact that some of the alpha particles were deflected.
   b. The second bullet point was inferred from the information that most of the alpha particles traveled straight through the metal foil, as if nothing were in their path.
   c. The third bullet point was inferred because as the alpha particles randomly struck the gold target, a few approached the nucleus of the atom head on. The positively charged alpha particles were strongly repelled by the nuclear charge

2.
   a. Marbles correspond to alpha particles
   b. Board corresponds to the gold foil target
   c. Unseen object corresponds to the atomic nucleus
   d. Traced path of the marble corresponds to the scattering angles of the alpha particles

3.



3. Knowing where the marble rolls in one side and out the other is an important first step for determining the size of the object and its position on the board.

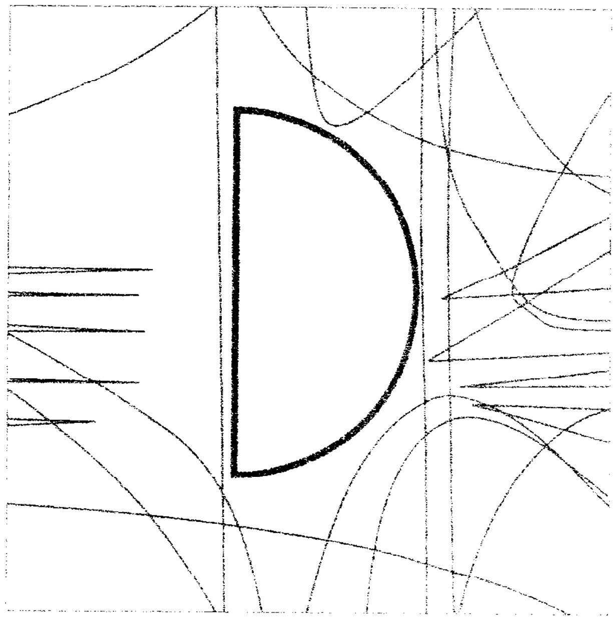
Post-Lab Questions

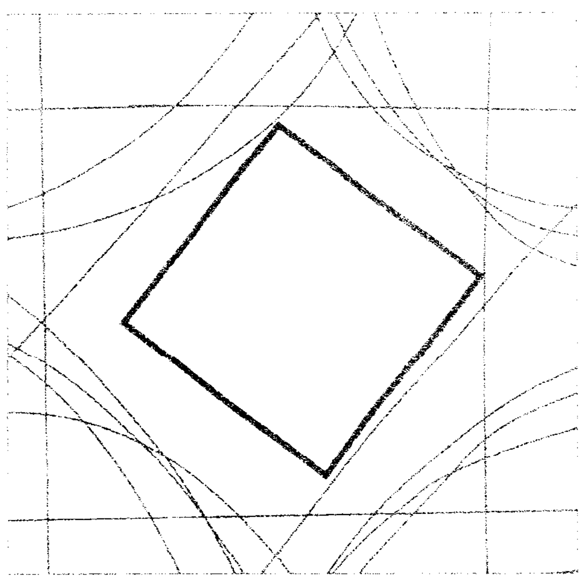
1. See sample data on next page. It is easiest to determine the overall size and position of the target. It was also relatively easy to deduce straight edges on the target that were perpendicular to the marble roll. It was more difficult to distinguish between curved edges and slanted straight edges.
2. The most obvious answer students will give is that the speed of the marble must be fast enough to pass through to the other side of the board if the target is not in its way. **Note:** the speed of the marble will affecthte angle of deflection (rebound path). If the marble is too slow, the rebound path or angle will change as friction forces slow it down further (WOW a good time to review forces and friction)

3. The targets used in this study were approximately ten times larger than the marbles. In general if the marble hits any part of the target it will be deflected. Thus the target will appear larger than it is by the diameter of the marble. Small pieces of metal shott give the best data but oh what a mess they make.

References;
Flinn chemTopic Labs
Volume 3
Atomic and Electron Structure

Sample Data





QN06-18

Psyching Out the System

(Student Page)

When scientists study any system they must ask two basic questions:

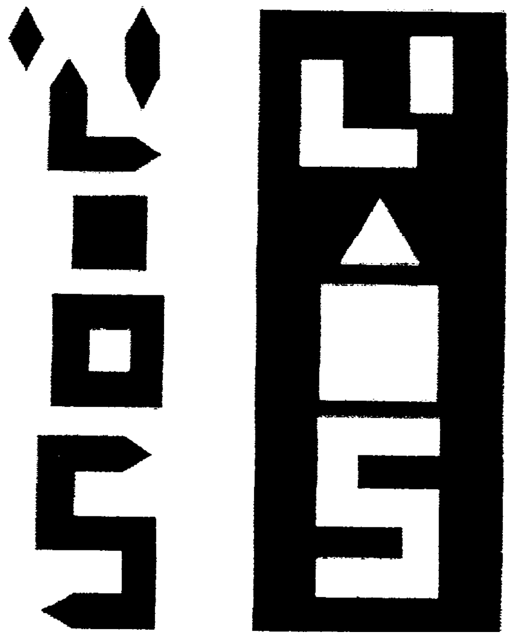
1. What are the basic objects, or "building blocks," from which this system is made?
2. What are the interactions between these objects?

The answer to these questions depends on the scale at which you study the system. Particle physics plays this game on the smallest possible scales -- seeking to discover the basic building blocks of all matter and the fundamental interactions between them.

The connecting rules of these interactions, or basic forces, explain why some composite objects are observed and others are not observed. The basic forces are as important as the "building blocks" in explaining data, and what does not happen is as important a clue as what does.

This puzzle shows the challenge that particle physicists face. Imagine that the puzzle presents information that was obtained about particles from an accelerator. The black figures represent objects that were observed, while the objects shown in white have not been observed. In this puzzle, "objects" are all two-dimensional shapes, and "interactions" are ways in which they can combine.

The shapes that are not observed provide important clues to the answers.



Write your answers in these spaces. Note that you need to answer both questions to explain why the objects that are not observed are not possible.

The observed figures are constructed from:

1.____

2.____

The rules for connecting these shapes are:

1.____

2.____

[Puzzle adapted from Helen Quinn, "Of Quarks, Antiquarks, and Glue." The Stanford Magazine, Fall, 1983, p.29.]

QN06-20

Psyching Out the System
Teacher Page

Goal:
To illustrate the universal method of analyzing a system in terms of its components and their interactions

General Information
In this activity students assume the role of scientists as they interpret data while playing a "puzzle shape" game that challenges them to evaluate objects that are hypothetically "observed" as well as those that are "not observed" this puzzle applies to all of science, not just particle physics. When scientists study any system they must begin with the same two basic questions:

1. What are the components of this system?
2. How do the components interact?

Through this exercise, students learn that the rules of interaction are as important as the "building blocks" in explaining data. In addition they become aware that what does NOT occur is often as important a clue as what DOES occur.

As students begin working on this activity, give them a hint that the components that they are looking for are two-dimensional shapes. After they find the shapes, point out that both the "observed" and the "not observed" could be built from the same shapes. Point out to the students that the answer to the second question must explain why some shapes are NOT observed.

When the students have completed the activity sheet, suggest that they draw additional objects using the building blocks and basic forces illustrated in the activity. They should indicate whether the shapes they have drawn would belong to the "observed" or "not observed" lists. This is a good opportunity to review that science is a dynamic process and the shapes drawn could be thn searched for in future data.

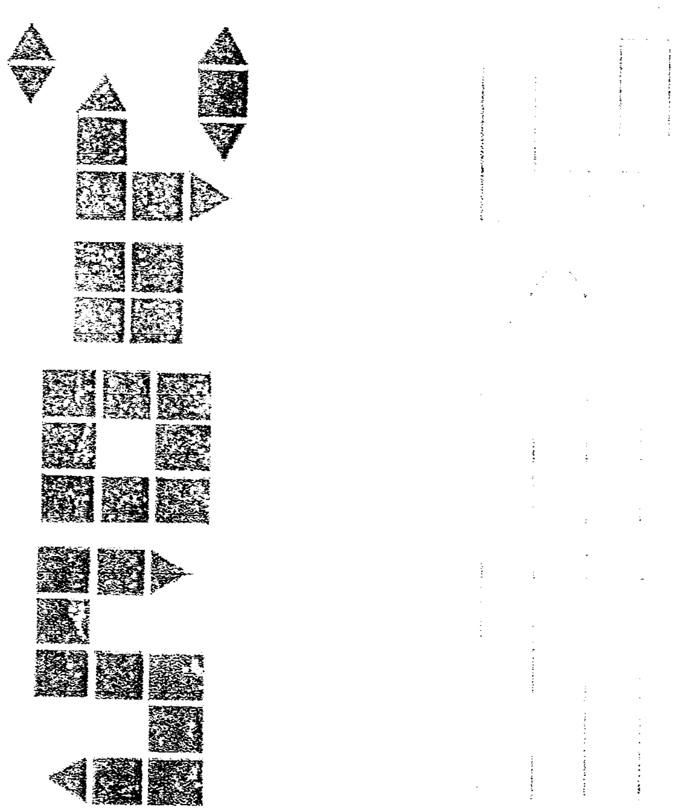
The building blocks are small squares and small equilateral triangles, both with the same side length. The rules for constructing these figures are that every triangle must form a single bond and every square must form two bonds with other constituents.

Some students may suggest that the answer is triangles only; this is acceptable as long as they also see that there are two different types of triangles (the second is an isosceles right triangle with the congruent sides the length of the side of the square.) the rules of interaction for the solution are that he right triangles form two types of bonds: one that is a pairing bond to another right triangle and the other one to the equilateral triangle. As with the other solution the equilateral triangles form a single bond.

Below you will find a correct solution to the puzzle. It would be a good idea to emphasize the interactions of the system.

This activity could be used in a chemistry classroom as an introduction to bonding. The discussion of the components of a bonding system and the interactions are a natural next step after this activity.

Observed | Not Observed



QN06-22

A Laboratory Exercise in Fundamental Units

The Standard Model or the Millikan Experiment

Introduction:

In this activity the students are to find the mass of the object that is common to a set of envelopes. This activity is analogous to the Millikan oil drop experiment. The Millikan Experiment and the Standard Model Both require that students recognize that charge and matter are observed in discrete units. This activity can be used as an introduction to either of these topics.

Discussion:

An understanding of the nature of fundamental particles helps students recognize both the complexity and simplicity of nature. Just as all the words in the English language are combinations of subsets of 26 letters; atomic physics showed that atoms of the many elements are combinations of three particles – the proton, neutron, and electron. As the number of "elementary particles" identified in cosmic ray showers and other high-energy interactions proliferated, some began to believe they were complex, composite particles created from a few, more fundamental particles. This activity will help students identify common elements of their "atoms" and also suggest that what is determined to be fundamental indeed has a substructure – an introduction to the Standard Model.

Purpose:

To find the smallest common mass in a set of envelopes.

Procedure:

You will be given a number of envelopes. **Do not open the envelopes!** Measure the mass of each envelope to the nearest 0.1 gram and record the mass on this sheet and on the board in front of the class. Also record the masses of all the other envelopes from your class. (An alternative method is to have each person enter their data into the calculator and then link and share data with each person. The sort function can then be used to plot the data)

Analysis:

List all the envelope masses in ascending order. Envelope #1 will be the lightest. From this list of sorted data construct a bar graph of envelope mass (vertical axis) as a function of envelope # (horizontal axis) on a separate piece of paper. Sketch the graph below

Questions:

1. What do you notice about the envelope masses on the finished graph?

2. List the "average" mass for each of the envelope "types."

3. What is the mass difference between the successive averages found in question 2?

4. What does this difference represent? Explain.

QN06-24

Table of Baryons

Particle	Symbol	Makeup	Rest mass MeV/c^2	Spin	B	S	Lifetime (seconds>	Decay Modes
Proton	p	uud	938.3	1/2	+1	0	Stable	...
Neutron	n	ddu	939.6	1/2	+1	0	920	$pe^-\bar{\nu}_e$
Lambda	Λ^0	uds	1115.6	1/2	+1	-1	2.6 $\times10^{-10}$	$p\pi^-$, $n\pi^0$
Sigma	Σ^+	uus	1189.4	1/2	+1	-1	0.8 $\times10^{-10}$	$p\pi^0$, $n\pi^+$
Sigma	Σ^0	uds	1192.5	1/2	+1	-1	6×10^{-20}	$\Lambda^0\gamma$
Sigma	Σ^-	dds	1197.3	1/2	+1	-1	1.5 $\times10^{-10}$	$n\pi^-$
Delta	Δ^{++}	uuu	1232	3/2	+1	0	0.6 $\times10^{-23}$	$p\pi^+$
Delta	Δ^+	uud	1232	3/2	+1	0	0.6 $\times10^{-23}$	$p\pi^0$
Delta	Δ^0	udd	1232	3/2	+1	0	0.6 $\times10^{-23}$	$n\pi^0$
Delta	Δ^-	ddd	1232	3/2	+1	0	0.6 $\times10^{-23}$	$n\pi^-$
Xi Cascade	Ξ^0	uss	1315	1/2	+1	-2	2.9 $\times10^{-10}$	$\Lambda^0\pi^0$
Xi Cascade	Ξ^-	dss	1321	1/2	+1	-2	1.64 $\times10^{-10}$	$\Lambda^0\pi^-$
Omega	Ω^-	sss	1672	3/2	+1	-3	0.82 $\times10^{-10}$	$\Xi^0\pi^-$, Λ^0K^-
Lambda	Λ^+_c	udc	2281	1/2	+1	0	2×10^{-13}	...

To Meson Table

aN06-25

Mesons

http://hyperphysics.phy-astr.gsu.edu/hbase/particles/meson.html#c1

Particle	Symbol	Anti-particle	Makeup	Rest mass MeV/c^2	S	C	B	Lifetime	Decay Modes
Pion	π^+	π^-	$u\underline{d}$	139.6	0	0	0	2.60 x10^{-8}	$\mu^+\nu_\mu$
Pion	π^0	Self	$\frac{u\bar{u}+d\bar{d}}{\sqrt{2}}$	135.0	0	0	0	0.83 x10^{-16}	2γ
Kaon	K^+	K^-	$u\underline{s}$	493.7	+1	0	0	1.24 x10^{-8}	$\mu^+\nu_\mu$, $\pi^+\pi^0$
Kaon	K^0_s	K^0_s	1*	497.7	+1	0	0	0.89 x10^{-10}	$\pi^+\pi^-$, $2\pi^0$
Kaon	K^0_L	K^0_L	1*	497.7	+1	0	0	5.2 x10^{-8}	$\pi^+e^-\underline{\nu}_e$
Eta	η^0	Self	2*	548.8	0	0	0	<10^{-18}	2γ, 3μ
Eta prime	$\eta^{0'}$	Self	2*	958	0	0	0	...	$\pi^+\pi^-\eta$
Rho	ρ^+	ρ^-	$u\underline{d}$	770	0	0	0	0.4 x10^{-23}	$\pi^+\pi^0$
Rho	ρ^0	Self	$u\underline{u}$, $d\underline{d}$	770	0	0	0	0.4 x10^{-23}	$\pi^+\pi^-$
Omega	ω^0	Self	$u\underline{u}$, $d\underline{d}$	782	0	0	0	0.8 x10^{-22}	$\pi^+\pi^-\pi^0$
Phi	φ	Self	$s\underline{s}$	1020	0	0	0	20 x10^{-23}	K^+K^-, $K^0\underline{K}^0$
D	D^+	D^-	$c\underline{d}$	1869.4	0	+1	0	10.6 x10^{-13}	K + _, e + _
D	D^0	$\underline{D}^0$	$c\underline{u}$	1864.6	0	+1	0	4.2 x10^{-13}	[K,μ,e] + _
D	D^+_s	D^-_s	$c\underline{s}$	1969	+1	+1	0	4.7 x10^{-13}	K + _
J/Psi	J/ψ	Self	$c\underline{c}$	3096.9	0	0	0	0.8 x10^{-20}	e^+e^-, $\mu^+\mu^-$...
B	B^-	B^+	$b\underline{u}$	5279	0	0	-1	1.5 x10^{-12}	D^0 + _
B	B^0	$\underline{B}^0$	$d\underline{b}$	5279	0	0	-1	1.5 x10^{-12}	D^0 + _
B_s	B_s^0	$\underline{B}_s^0$	$s\underline{b}$	5370	0	0	-1	...	B^-_s + _
Upsilon	Υ	Self	$b\underline{b}$	9460.4	0	0	0	1.3 x10^{-20}	e^+e^-, $\mu^+\mu^-$..

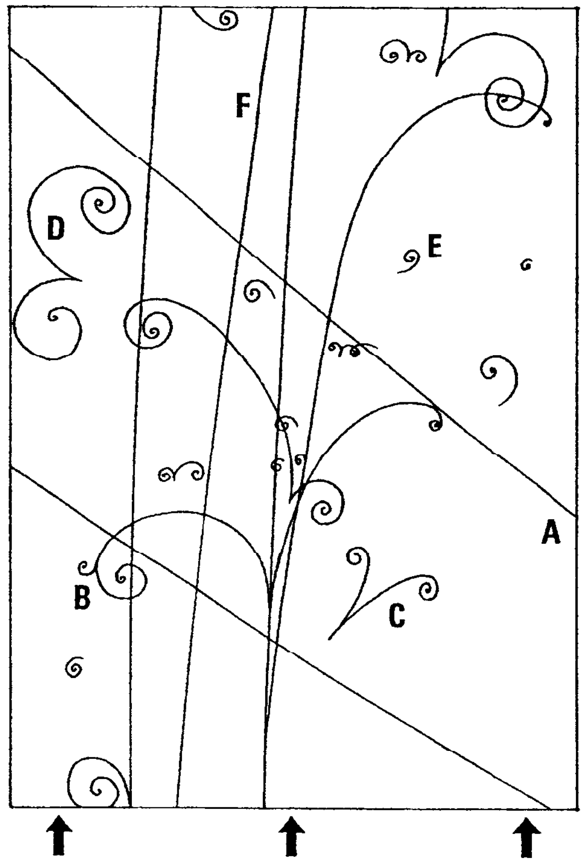
QNOC-26

Tracking Particle Paths

NOVA Activity **The Elegant Universe**

Donald Glaser invented the bubble chamber in 1952. Inside the bubble chamber a superheated liquid, such as liquid hydrogen, is expanded just before particles are beamed through. The beamed particles—and some of the interactions they produce—ionize the atoms in the liquid, resulting in a series of bubbles along the trajectory of the particles. The bubbles make the tracks of the particles visible. The events are photographed. Once the events have occurred, the liquid is recompressed for the next particle burst. The following are some facts about how some tracks are formed:

- Only electrically charged particles leave trails. Protons, the particles beamed through the liquid in this example, are positively charged particles.
- Particles from outside the bubble chamber, such as cosmic rays, can also be recorded in the liquid.
- A magnetic field throughout the liquid in the chamber causes particle paths to bend. Particles with opposite charges produce paths that curve in opposite directions. In this representation, negatively charged particle trails curl left and positively charged particle trails curl right.
- The beamed particles all originated from the same direction and entered the liquid at the same speed.
- When a high-energy photon—which has no charge—interacts with a charged particle, the interaction can produce a pair of oppositely charged particles. This usually results in an electron-positron pair, a V-shaped trail in which each end of the V spins off in an opposite direction and spirals inward.
- Particles with less momentum, or those that have less mass, produce trails that curve more from the point *at which they were produced.* Particles with greater momentum, or those that are more massive, produce paths that curve less from the point of production. In the case of a particle pair, for example, a pair with greater momentum (or mass) will result in a longer, narrower V shape than a pair with less momentum (or mass).
- A photon that knocks an electron out of an atom creates a single track that bends to the left and spirals inward. This product is called a Compton electron.



Direction of Particle Beam

QN06-27

Name______________________________________date_______________

Report on Bubble Chamber Basics

Physicists once used a device called a bubble chamber to record particle interactions. The illustration represents the kinds of particle interactions that were4 commonly re3corded by bubble chamber dete ctors. Today, bubble chambers have been replaced y detectors that can measure energies a thousand times larger, and can look for particles a billion times more rare. However, bubble chamber tracks are useful to show the kinds of interactions that can occur between particles. Read the information in the *Tracking Particle Paths* activity sheet to learn more about bubble chambers and the kinds of tracks they produce. Then answer the questions.

1. a. Which letter(s) represent electron-positron pairs?_______________
   b. Which side of the pair(s) represent the electron?____________
   c. Which side represents the positron?____________________
   d. Explain your answer:

2. Which track(s) show a Compton electron that has been knocked out of an atom?____________ Explain :

3. Assuming that tracks C and D were formed by the same kind of particles and are the actual lengths shown, which pair had greater momentum?______Explain:

4. a. Identify a track that did not come from the particle beam:______
   b. How do you know?

   c. Where might this track have originated?

5. What might track F represent?_____________________Explain:

6. What were the main types of particle interactions recorded?

7. What particles would not leave tracks in a bubble chamber?

8. How can you detect where unseen particles would have been in the illustration?

QN06-28

Name KEY date

Report on Bubble Chamber Basics

Physicists once used a device called a bubble chamber to record particle interactions. The illustration represents the kinds of particle interactions that were4 commonly re3corded by bubble chamber dete ctors. Today, bubble chambers have been replaced y detectors that can measure energies a thousand times larger, and can look for particles a billion times more rare. However, bubble chamber tracks are useful to show the kinds of interactions that can occur between particles. Read the information in the *Tracking Particle Paths* activity sheet to learn more about bubble chambers and the kinds of tracks they produce. Then answer the questions.

Scoring Points

20 (5pts each)

1. a. Which letter(s) represent electron-positron pairs? (B) ?C D
   b. Which side of the pair(s) represent the electron? left
   c. Which side represents the positron? right
   d. Explain your answer: magnetic field is positive on left, negative on right, and opposites attract

10 — 2. Which track(s) show a Compton electron that has been knocked out of an atom? E Explain : curls like electron

10 — 3. Assuming that tracks C and D were formed by the same kind of particles and are the actual lengths shown, which pair had greater momentum? C Explain: C goes straighter longer

10 — 4. a. Identify a track that did not come from the particle beam: A
   b. How do you know? enters from a different direction

10 — c. Where might this track have originated? cosmic ray – proton because it's moving to the right

10 — 5. What might track F represent? beam particle Explain: hasn't interacted —comes from beam source

10 — 6. What were the main types of particle interactions recorded? Compton electrons + electron-positiron pairs

10 — 7. What particles would not leave tracks in a bubble chamber? photons, neutral particles: neutron, neutrino

10 — 8. How can you detect where unseen particles would have been in the illustration? where tracks suddenly appear or disappear

total = 100 pts.

QN06-29

up

down

charm

strange

top

bottom

GNOC-30

gravity

electromagnetic

weak

Forces of Interaction

strong

Fundamental particles

QN06-31

baryons	mesons
Forces of Interaction	3 Quarks
2 quarks	leptons
quarks	

QN06-32

electron neutrino	muon	muon neutrino
tau neutrino	electron	Tau

All Physicists Have Charm!

Name ____________________

Now that you have heard a little bit about Particles and Interactions, let's see if you can make sense of all the unusual names.

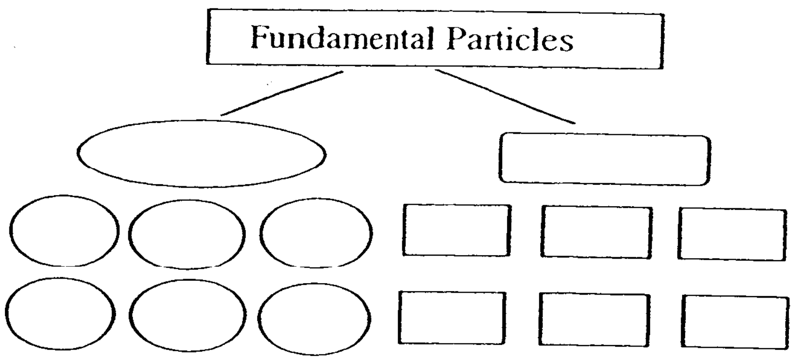
What are the two basic questions that people have always asked?

1.

2.

Draw and label all the parts of an atom that you can.

Fill in this chart the best that you can without looking at your notes or anything else. When your teacher tells you, consult with your neighbor and fill in more.



Composite Particles

Combinations of _____ make composite particles, called [ ] and [ ], made of

_ _ _   _ _

Forces or Interactions

1. ____________ 2. ____________ 3. ____________ 4. ____________

Draw lines from each force to the fundamental particles with which it interacts.

What questions do you have?

GMCC-34
QN-19

All Physicists Have Charm!

Don't "grade" this, but use it for the students to organize their thoughts and all the new words. This is a good activity for pairs of students. The answers may not be in the same order as below. Some students may be able to organize the quarks into "families", etc. Use the chart of the Standard Model to check different ideas. Students should be asking why the particles are grouped the way that they are. Leave some unanswered questions at this time. You might want to come back to this later in the unit.

Now that you have heard a little bit about Particles and Interactions, let's see if you can make sense of all the unusual names.

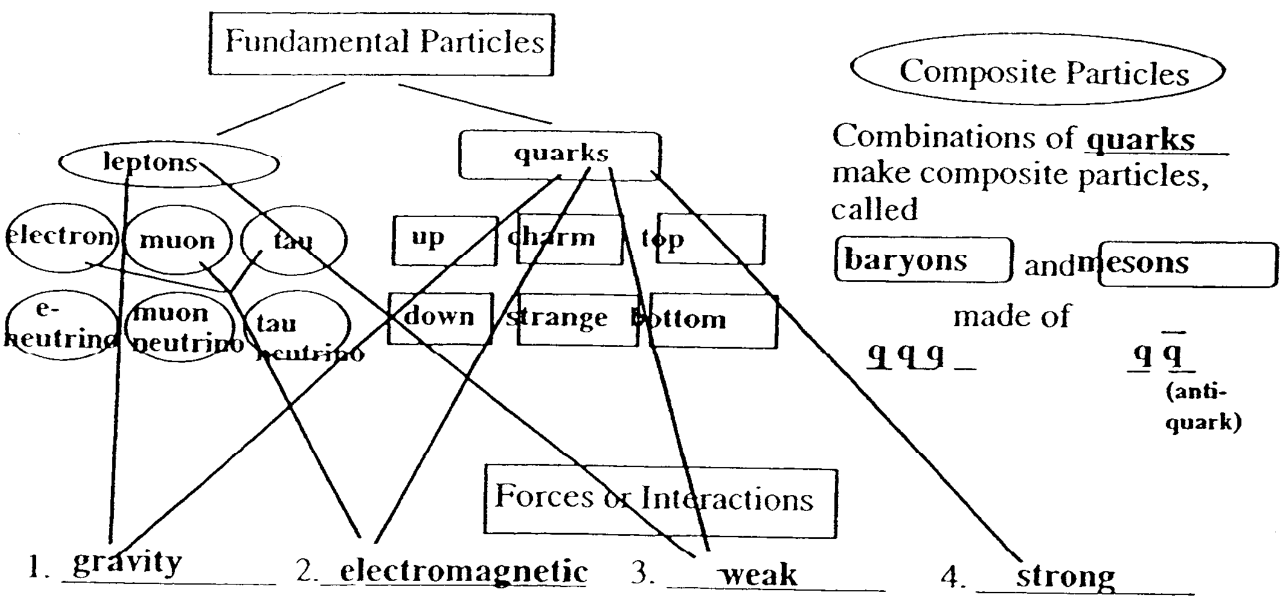
What are the two basic questions that people have always asked?

1. **Of what is the world made ?**
2. **What holds it together?**

Draw and label all the parts of an atom that you can.

Students should show the nucleus with protons and neutrons in it. They should show quarks in the protons and neutrons. Electrons should be outside the nucleus.

Fill in this chart the best that you can without looking at your notes or anything else. When your teacher tells you, consult with your neighbor and fill in more.



Draw lines from each force to the fundamental particles with which it interacts.

What questions do you have?

QN06-35
PN-20

Professional Development Opportunities and Organizations

Marty Peters
Summer 2006

Professional Development

- Workshops: NSF, NASA, AP
- Research: DOE, NSF
- QuarkNet
  http://quarknet.fnal.gov
- AEP/PSO
- Local/State
- NSTA Listings
- Self-Designed

Grading Opportunities

- AP
- NBPTS (National Board for Professional Teaching Standards)
- Miscellaneous College Board and National Testing Program

Professional Organizations

- NSTA www.nsta.org
- OSTA
- AAPT www.aapt.org

QN06-37

Detectors and Accelerators

Marty Peters
Summer 2006

Detectors

- Detectors may be used to visualize, measure, or analyze particles and other forms of radiation. Properties detected include charge, mass, and momentum. They are often based on ionization of matter or luminescence.

Cloud Chamber

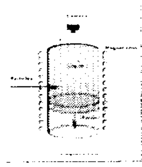
- Gas-filled. Super-saturated vapor
- Droplets form on ions generated by passing particle
- ~1900 C.T.R. Wilson

Source: www.scienceline.net

QN06-38

Bubble Chamber

- Superheated liquid
- Trails of gas bubbles from ionizing particles
- 1952 Donald Glaser



Source: Wikipedia

Photographic Plates

- Light-sensitive emulsion
- Blackened by radiation
- 1910's Victor Franz Hess – cosmic radiation left traces on stacks of plates
- Mountains; balloons

Source: faculty.washington.edu

Photomultiplier Tube (PMT)

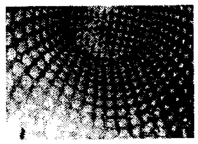
- Vacuum tube
- Converts light to electrical energy
- Amplifies

Source: www.answers.com

QN06-39

Cherenkov Detector

- 1934 Cherenkov
- Charged particles pass through transparent medium > speed of light in that medium [sonic boom]
- Radiating light particles vs non-radiating heavy



Source: neutrino.kek.jp

Ionization/Geiger-Mueller

- 1908 Hans Geiger
- Inert gas & organic vapor
- Cathode (metal walls)
- Anode (wire)
- 100's v; 0 amp
- Radiation ionizes gas
- Current pulse

Source: www.answers.com

Scintillation Counter

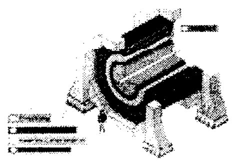
- Radiation strikes phosphor
- Absorption & reemission
- Tiny visible flashes
- Based on Becquerel's phosphorescence

Source: www.ipj.gov.pl

QN06-40

Calorimeters

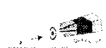
- Measure energy



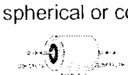
Source: particleadventure.org

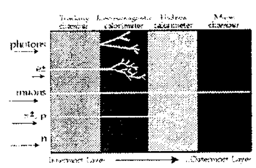
Detector Format

- Fixed Target – cone shaped
- Colliding Beams – spherical or cone

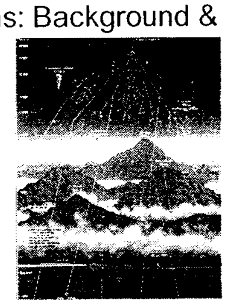


Source: particleadventure.org





Sources of Particles and/or Photons: Background & Cosmic



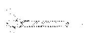
Source: lyoinfo.in2p3.fr/ manoir/lsm_eng.html

QN06-41

Sources of Particles and/or Photons: Radioactive Sources

Source: www.kiddofspeed.com

Sources of Particles and/or Photons: Accelerators



Linear – Fixed Target or Collider

Circular

Source: particleadventure.org

QN06-42

Icebreaker Activity:
A Cosmic Ray Shower Puzzle

If you are not familiar with the term "icebreaker" it is generally used to describe an activity at the beginning of a meeting, workshop or class used to "break the ice" or get everyone talking to one another.

When a cosmic ray interacts with the Earth's atmosphere it creates secondary particles. These particles then interact in the atmosphere and create even more particles, which then create more particles and on and on. This process, called a {\it cosmic ray shower}, propagates through the atmosphere until eventually, some of the particles reach the ground.

This icebreaker activity involves putting together puzzle pieces to construct a representation of a cosmic ray shower.

Use this activity to peak interest and start a conversation about cosmic rays and cosmic ray showers. Break the audience into groups of three or four and have each group work on the puzzle together.

Ask each group what they think they are putting together a picture of. Some may have no idea, that is okay.

How might they know which way is up? Why do some of the lines stop midway?

Ask questions like these to get your audience wondering about cosmic rays. Then, visit the CHICOS classroom page for classroom activities related to cosmic rays and the CHICOS project.

Materials

To prepare this activity you will need the following materials:

- Cosmic Ray Shower Puzzle
- Cosmic Ray Shower Key
- Paper Cutter or Scissors

Puzzle Preparation

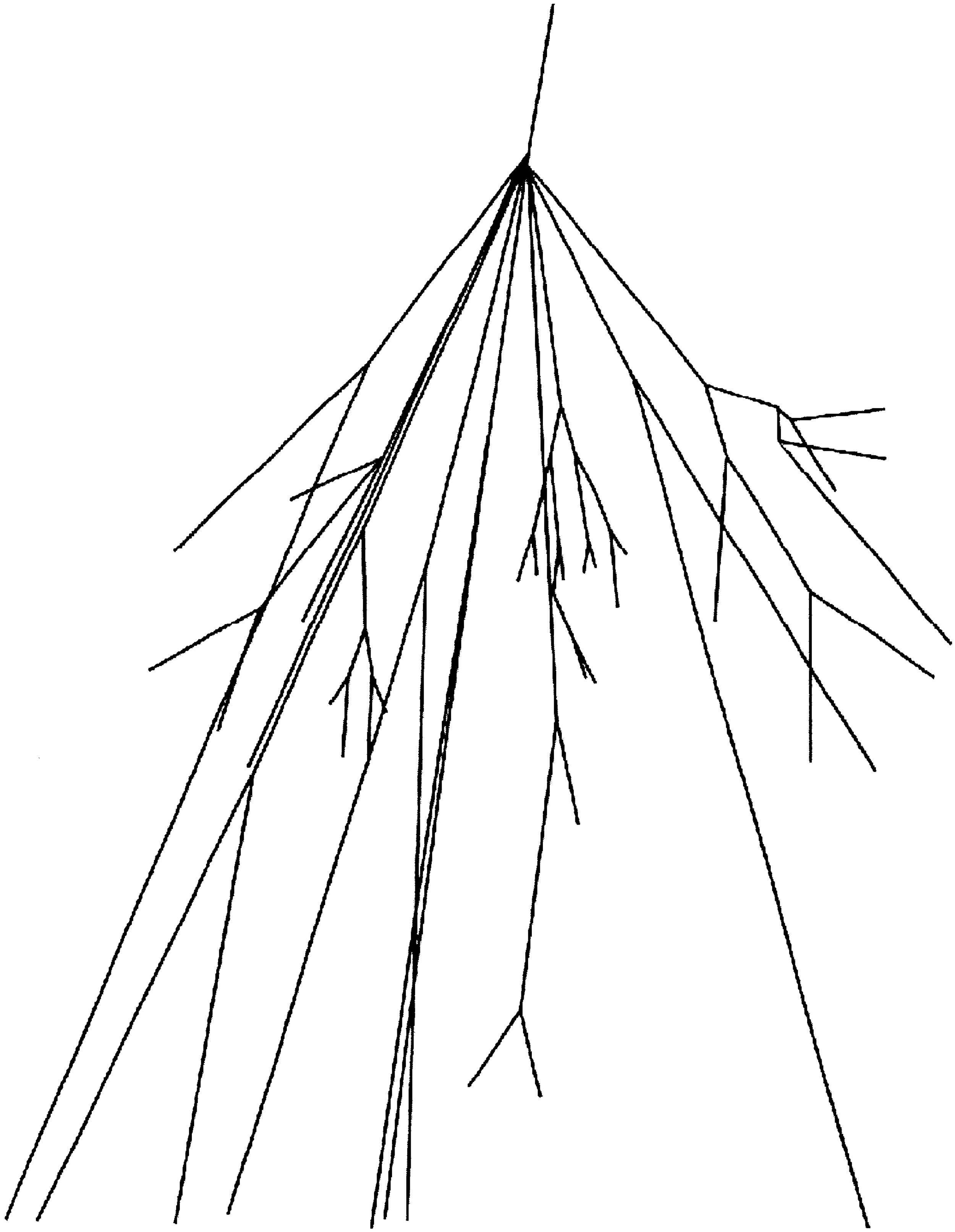
- Print the cosmic ray shower puzzle page.

- Make enough copies of this page to accommodate the number of groups you'll have.

- Fold the puzzle page down the middle as marked.
- Cut the page into five pieces where indicated by CUT HERE. Carefully trim each piece just above and below the black lines. Do not leave any white border.
- Cut each piece in two along the fold to make 9 total pieces (discard the bland white piece).

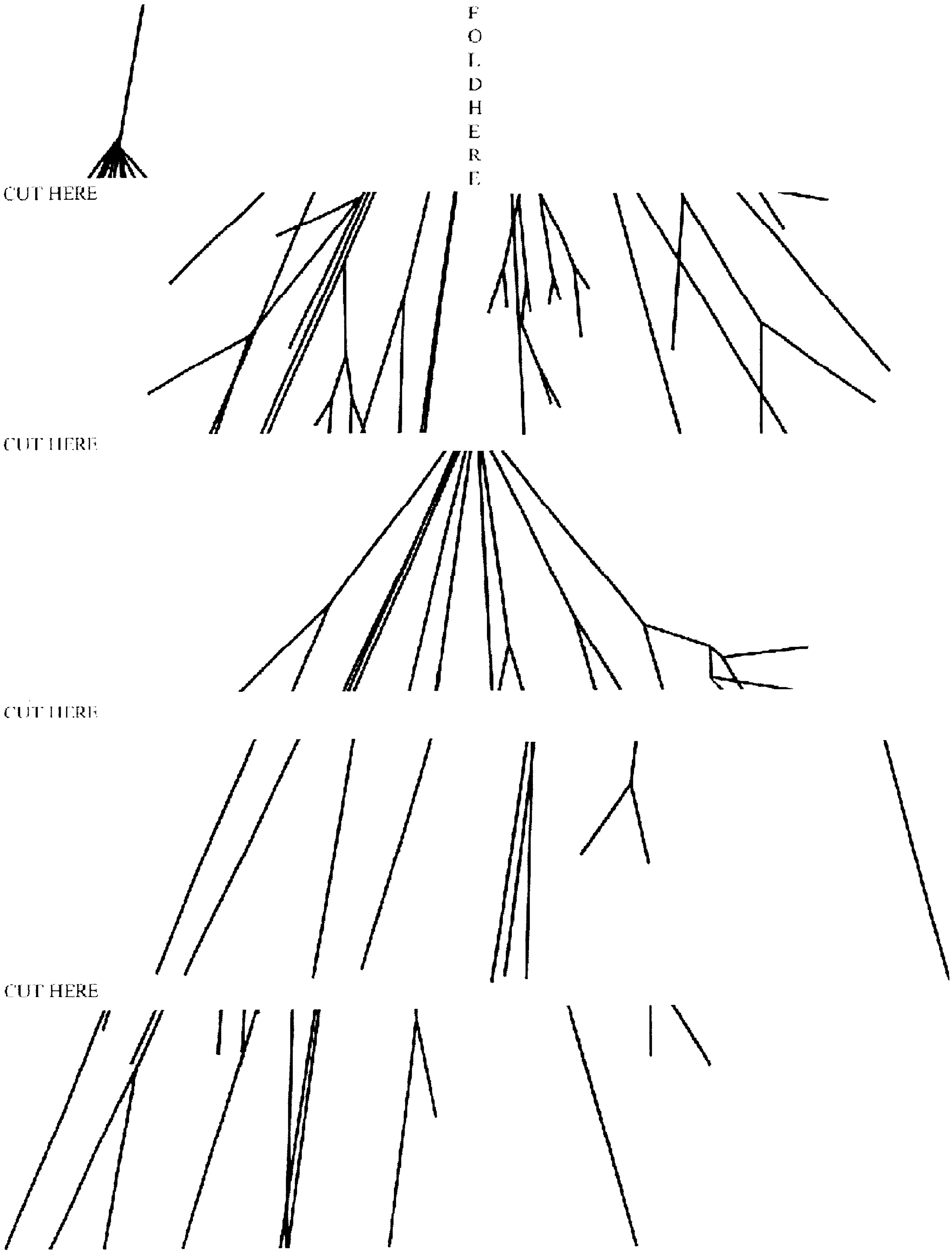
This is the cosmic ray shower puzzle. Distribute a puzzle piece set to each group and allow them to reconstruct the shower image. Use the complete shower page as a key to see how everyone did.

CHICOS Classroom   CHICOS Homepage



QN06-45

1



QN06-46

Name ______________________ Period ________ Date ________

CONSERVATION OF MOMENTUM: A COLLISION IN TWO DIMENSIONS 16

In Investigation 15, Conservation of Momentum: Internal Force, the momenta of two bodies moving in a straight line were measured. Is momentum conserved in other kinds of collisions?

A steel sphere rolls down a ramp and collides with a second sphere. Both spheres fall to the floor where their distances from the point of collision are measured. Listen to the sound made by the balls striking the floor. Note that the time required for the target sphere to reach the floor is the same as the time required for the incident sphere to fall from the end of the ramp to the floor. We will call this time of fall our standard time unit. The horizontal distance a ball travels during this time period depends only upon the horizontal velocity of the sphere. The horizontal distance is the distance from the point on the floor just below the initial position of the sphere to the point where it lands. The horizontal distance can be measured directly along the floor.

When spheres of equal mass are used for the target sphere (m) and the incident sphere (m'), the mass of each can be designated one mass unit ($m = m' = 1$). The horizontal velocity of each sphere is proportional to the horizontal distance traveled by each sphere. Therefore, this same horizontal distance can be used to represent the momentum of each sphere because the mass is one and momentum is mv.

Equipment

- collision in two dimensions apparatus
- meter stick
- tracing paper
- carbon paper
- C-clamp
- masking tape
- protractor

Notice on your apparatus the point from which the plumb line is suspended. It may be either from the incident sphere position or from the target sphere position. You will need to vary the investigation accordingly.

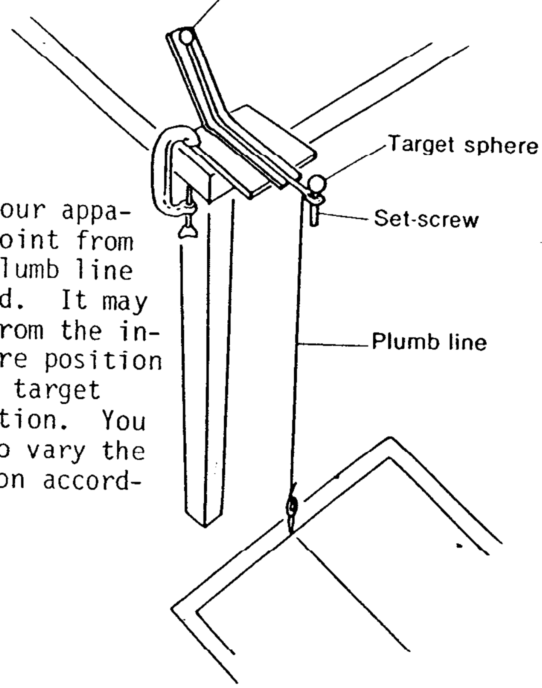


Figure 16-1. The result of the collision of the two spheres is recorded on the paper below the apparatus. The position of the target sphere is adjusted so that a glancing collision is obtained.

GW06-47

Objectives

During this investigation you will
- test the law of conservation of momentum in two dimensions.
- verify that momentum is a vector quantity.

Procedure

1. Arrange the apparatus as shown in Figure 16-1. Notice that the set-screw at the bottom of the ruler-ramp has a depression in its top. This is the resting place for the target sphere before each collision. Place the depression in the set-screw directly in front of the groove in the ruler and about one radius of the steel sphere away from the groove. Before beginning the experiment, roll a steel sphere down the ramp. Start the sphere about 25 cm from the bottom of the ramp. Watch the sphere as it rolls over the set-screw and adjust the screw so that the sphere just clears it.
2. Tape four pieces of carbon paper, each measuring 22 cm by 28 cm, together to form a large sheet of carbon paper measuring 44 cm by 56 cm. Do the same with four sheets of tracing paper. Put the carbon paper on the floor, carbon side up, with the tracing paper directly over it. Place the sheets in such a way that the center of one end of the paper is just below the plumb line. Tape the paper in place. Mark the point below the bob on the paper. Label this point *0*.
3. Without placing a target sphere on the set-screw, roll a steel sphere from near the top of the ramp several times. Roll this incident sphere from the same place each time and mark the points on the tracing paper where the sphere lands. Circle the cluster of points.
4. Adjust the position of the depression in the set-screw so that the incident sphere will collide with the target sphere at an angle. (See Figure 16-2.) You will need to extend the set-screw to make the adjustment. Check to be sure that the two spheres will be exactly the same height from the floor at the time of collision.

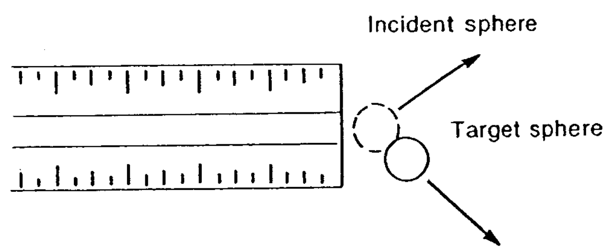


Figure 16-2. Adjust the position of the target sphere so that the two spheres are deflected at an angle.

5. Using a steel sphere as an incident sphere and a steel sphere of equal mass as a target sphere, try several collisions. Remember to roll the sphere each time from the same height you used previously. Circle and label the clusters of points where the incident sphere and the target sphere hit the paper.
6. Draw a vector from the zero point to a spot in the center of the first cluster of points. This vector represents the original momentum of the incident sphere. Label the vector p_0. Draw a second vector from the zero point to the center of the cluster of points where the target sphere landed. Label this vector p_{target}.

QN06-48

Name ______________________________ Period ________ Date ________

7. Draw the third vector from point zero to the center of the circle of points where the incident sphere landed. Label this vector $p_{incident}$.

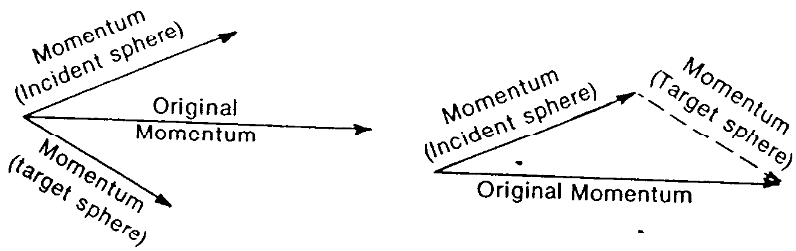


Figure 16-3. Move the vectors in a parallel manner until they begin at a single point. Then add the momentum of the incident sphere to the momentum of the target sphere. The resultant should equal the original momentum of the incident sphere before the collision.

8. Add the vector representing the momentum of the target sphere to the vector representing the momentum of the incident sphere to determine the total momentum after the collision.
9. Move the position of the target sphere and repeat Steps 4–8.

Interpretation

1. Include sketches of the results of your investigation.

QN06-49

For each position of the target sphere, compare the resultant of the sum of the final momenta of the target sphere and the incident sphere with the original momentum of the incident sphere. Explain your findings.

For each trial, measure the angle formed between the two final momentum vectors. Can you make any generalization?

Extensions

Repeat Steps 4–9 of the Procedure, using the same incident sphere and a glass sphere as the target sphere. In this case, the horizontal distances still represent velocity vectors, but not momentum vectors. To convert the velocity vectors to momentum vectors, you will need to find the *relative* masses of the two spheres. Adjust the length of the velocity vector of the target sphere and complete questions 1–3 of Interpretation.

To calculate the momentum of a sphere, it is necessary to know its mass and horizontal velocity. Measure the mass with a balance. Velocity can be determined using $v_h = d_h/t$. The horizontal travel time is just equal to the time it takes the sphere to hit the floor. This time can be determined by measuring the distance from the top of the set-screw (d_v) to the floor and substituting in the equation $d_v = \frac{1}{2} g t^2$. Note that t will be the same for all your calculations. Calculate the original momentum for the incident sphere and the final momenta for the incident and target spheres using data from several trials with both equal and unequal spheres. Find the resultant of the two final momenta in each trial and compare it to the original incident momentum.

3 DO K.E. before + after.
Is Collision elastic?

QN06-50

Name ______________________ Period ________ Date ________

CONSERVATION OF MOMENTUM: A COLLISION IN TWO DIMENSIONS 16

In Investigation 15, Conservation of Momentum: Internal Force, the momenta of two bodies moving in a straight line were measured. Is momentum conserved in other kinds of collisions?

A steel sphere rolls down a ramp and collides with a second sphere. Both spheres fall to the floor where their distances from the point of collision are measured. Listen to the sound made by the balls striking the floor. Note that the time required for the target sphere to reach the floor is the same as the time required for the incident sphere to fall from the end of the ramp to the floor. We will call this time of fall our standard time unit. The horizontal distance a ball travels during this time period depends only upon the horizontal velocity of the sphere. The horizontal distance is the distance from the point on the floor just below the initial position of the sphere to the point where it lands. The horizontal distance can be measured directly along the floor.

When spheres of equal mass are used for the target sphere (m) and the incident sphere (m'), the mass of each can be designated one mass unit ($m = m' = 1$). The horizontal velocity of each sphere is proportional to the horizontal distance traveled by each sphere. Therefore, this same horizontal distance can be used to represent the momentum of each sphere because the mass is one and momentum is mv.

Equipment

collision in two dimensions apparatus
meter stick
tracing paper
carbon paper
C-clamp
masking tape
protractor

Although this investigation is one of the most difficult to explain to the students, it is also one of the most effective investigations that they will attempt. When they add the two vectors representing the momenta of the two spheres after the collision and find that they agree with the original momentum of the single sphere, the entire purpose of the investigation becomes clear. A pre-lab discussion is essential.

Notice on your apparatus the point from which the plumb line is suspended. It may be either from the incident sphere position or from the target sphere position. You will need to vary the investigation accordingly.

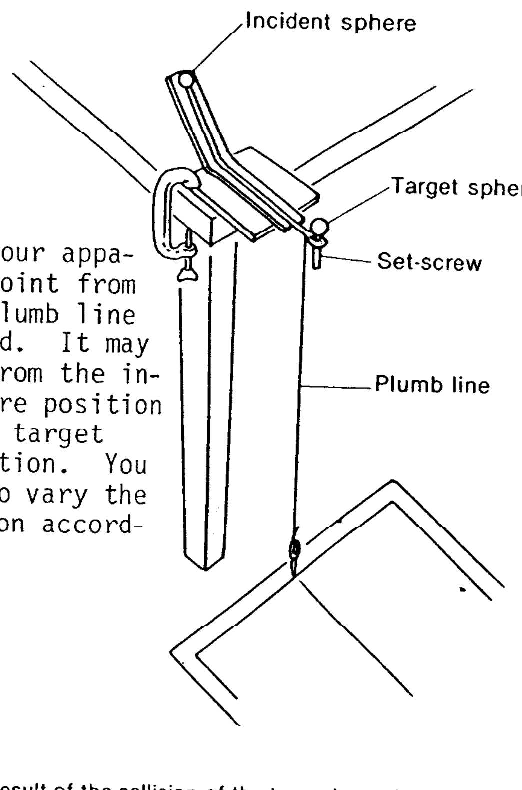


Figure 16-1. The result of the collision of the two spheres is recorded on the paper below the apparatus. The position of the target sphere is adjusted so that a glancing collision is obtained.

QN06-51

To a large extent, the carbon paper is wasted. Try to locate a source of used carbon paper. If you have a computer room in the school or other nearby facility, they can usually furnish you with an abundant supply of left-over carbon paper that is hardly marked. This carbon paper is very satisfactory.

Objectives

During this investigation you will
- test the law of conservation of momentum in two dimensions.
- verify that momentum is a vector quantity.

Procedure

1. Arrange the apparatus as shown in Figure 16–1. Notice that the set-screw at the bottom of the ruler-ramp has a depression in its top. This is the resting place for the target sphere before each collision. Place the depression in the set-screw directly in front of the groove in the ruler and about one radius of the steel sphere away from the groove. Before beginning the experiment, roll a steel sphere down the ramp. Start the sphere about 25 cm from the bottom of the ramp. Watch the sphere as it rolls over the set-screw and adjust the screw so that the sphere just clears it.
2. Tape four pieces of carbon paper, each measuring 22 cm by 28 cm, together to form a large sheet of carbon paper measuring 44 cm by 56 cm. Do the same with four sheets of tracing paper. Put the carbon paper on the floor, carbon side up, with the tracing paper directly over it. Place the sheets in such a way that the center of one end of the paper is just below the plumb line. Tape the paper in place. Mark the point below the bob on the paper. Label this point *0*.
3. Without placing a target sphere on the set-screw, roll a steel sphere from near the top of the ramp several times. Roll this incident sphere from the same place each time and mark the points on the tracing paper where the sphere lands. Circle the cluster of points.
4. Adjust the position of the depression in the set-screw so that the incident sphere will collide with the target sphere at an angle. (See Figure 16–2.) You will need to extend the set-screw to make the adjustment. Check to be sure that the two spheres will be exactly the same height from the floor at the time of collision.

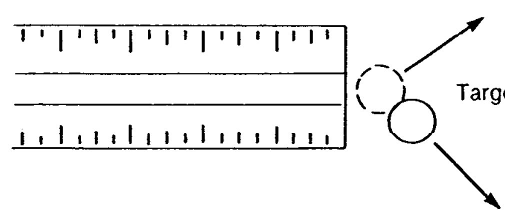


Figure 16–2. Adjust the position of the target sphere so that the two spheres are deflected at an angle.

5. Using a steel sphere as an incident sphere and a steel sphere of equal mass as a target sphere, try several collisions. Remember to roll the sphere each time from the same height you used previously. Circle and label the clusters of points where the incident sphere and the target sphere hit the paper.
6. Draw a vector from the zero point to a spot in the center of the first cluster of points. This vector represents the original momentum of the incident sphere. Label the vector p_0. Draw a second vector from the zero point to the center of the cluster of points where the target sphere landed. Label this vector p_{target}.

QN06-52

Name ______________________ Period ________ Date ________

7. Draw the third vector from point zero to the center of the circle of points where the incident sphere landed. Label this vector $p_{incident}$.

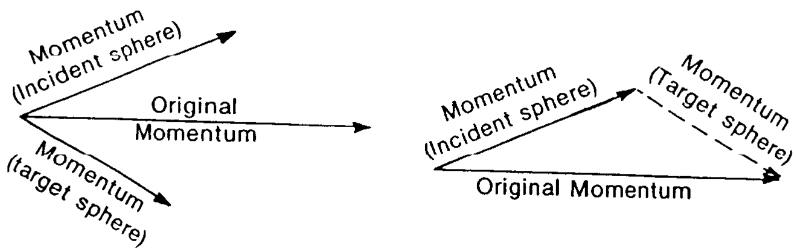
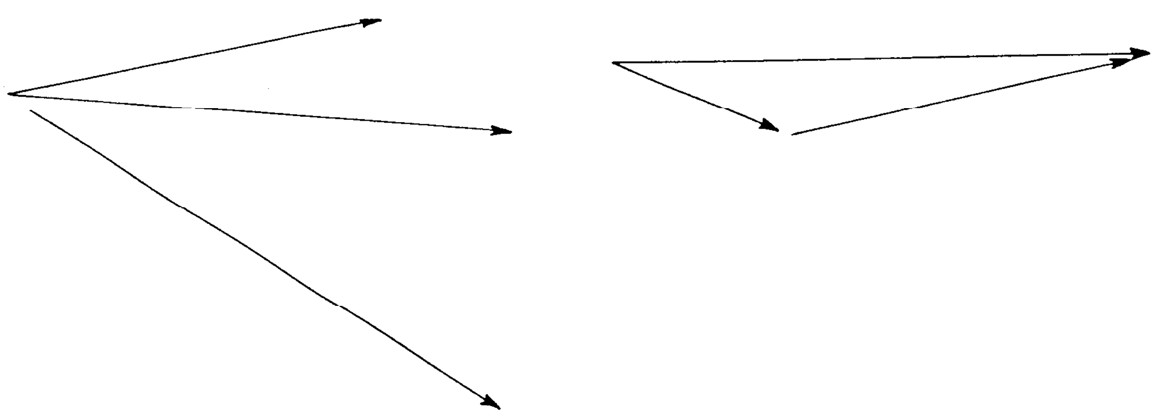


Figure 16-3. Move the vectors in a parallel manner until they begin at a single point. Then add the momentum of the incident sphere to the momentum of the target sphere. The resultant should equal the original momentum of the incident sphere before the collision.

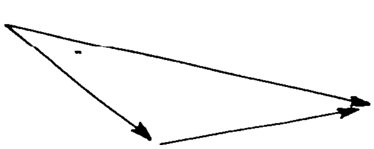
8. Add the vector representing the momentum of the target sphere to the vector representing the momentum of the incident sphere to determine the total momentum after the collision.
9. Move the position of the target sphere and repeat Steps 4–8.

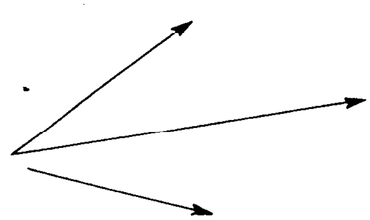
Interpretation

1. Include sketches of the results of your investigation.



Space is important because
both spheres do not start
at the same point.





2. For each position of the target sphere, compare the resultant of the sum of the final momenta of the target sphere and the incident sphere with the original momentum of the incident sphere. Explain your findings.

The vector sum after the collision is very close to the momenta of the incident sphere and target before collision.

3. For each trial, measure the angle formed between the two final momentum vectors. Can you make any generalization?

The angles should be close to 90°.

Pre-lab discussion:

Emphasize that it takes each sphere the same time to fall to the floor. Lead students to understand that the distance traveled by each sphere during this one unit of time is numerically the same as its velocity. Make clear that because the masses of both spheres are equal, it is possible to call the mass of each one mass unit. Therefore, the momentum of each is one mass unit multiplied by its velocity, which is its distance (numerically). Hence, the distance accurately represents the momentum of each sphere. When the two distances are allowed to be vectors representing the momenta, they will add up to the original momentum of the first sphere.

One important aspect of this investigation is to help the students become aware that a unit of measurement is primarily a constant.

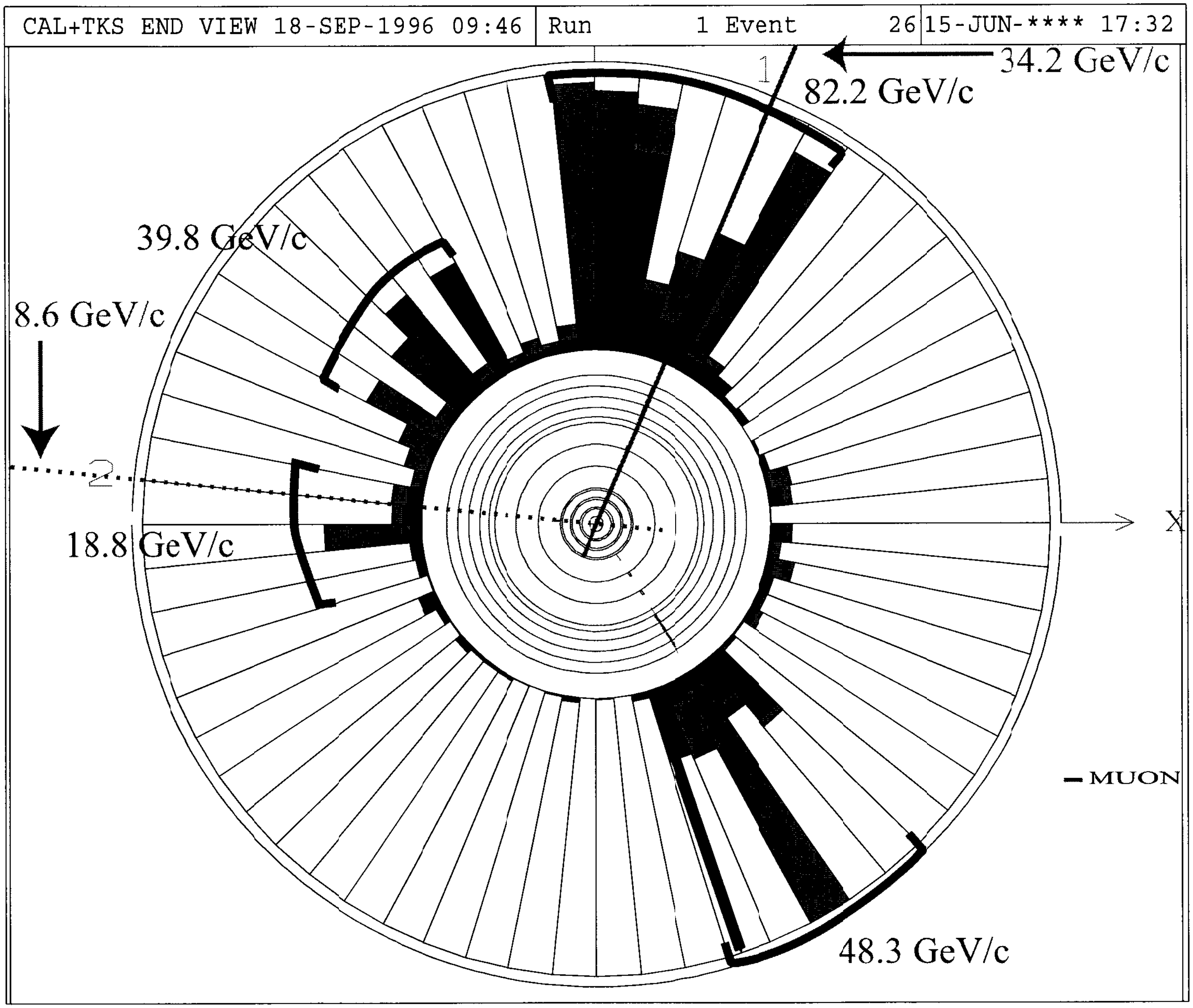
m = 8.4
h = 91 cm

Extensions

1. Repeat Steps 4–9 of the Procedure, using the same incident sphere and a glass sphere as the target sphere. In this case, the horizontal distances still represent velocity vectors, but not momentum vectors. To convert the velocity vectors to momentum vectors, you will need to find the *relative* masses of the two spheres. Adjust the length of the velocity vector of the target sphere and complete questions 1–3 of Interpretation.

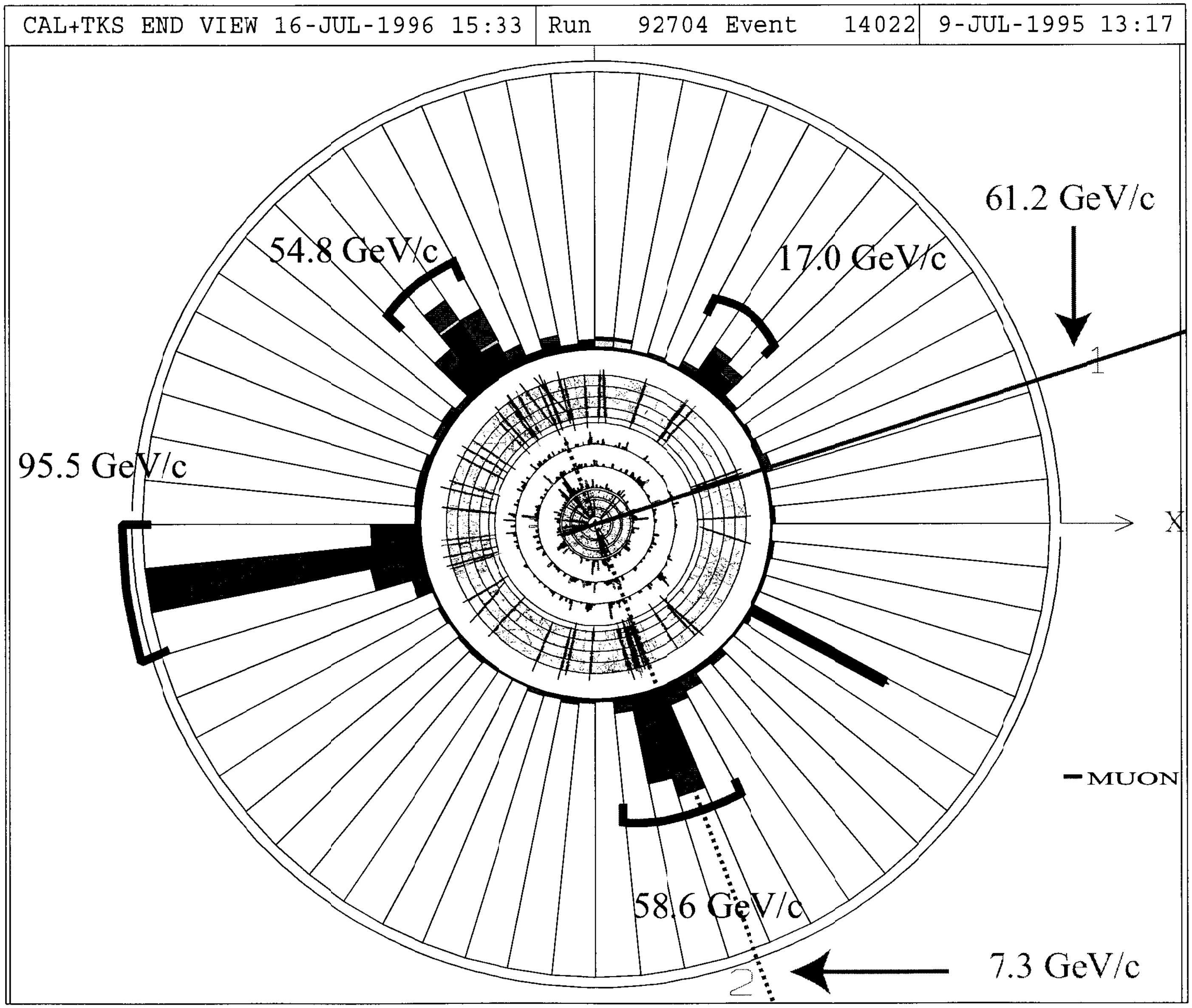
2. To calculate the momentum of a sphere, it is necessary to know its mass and horizontal velocity. Measure the mass with a balance. Velocity can be determined using $v_h = d_h/t$. The horizontal travel time is just equal to the time it takes the sphere to hit the floor. This time can be determined by measuring the distance from the top of the set-screw (d_v) to the floor and substituting in the equation $d_v = \frac{1}{2}gt^2$. Note that t will be the same for all your calculations. Calculate the original momentum for the incident sphere and the final momenta for the incident and target spheres using data from several trials with both equal and unequal spheres. Find the resultant of the two final momenta in each trial and compare it to the original incident momentum.

D-Zero Detector at Fermi National Accelerator Laboratory



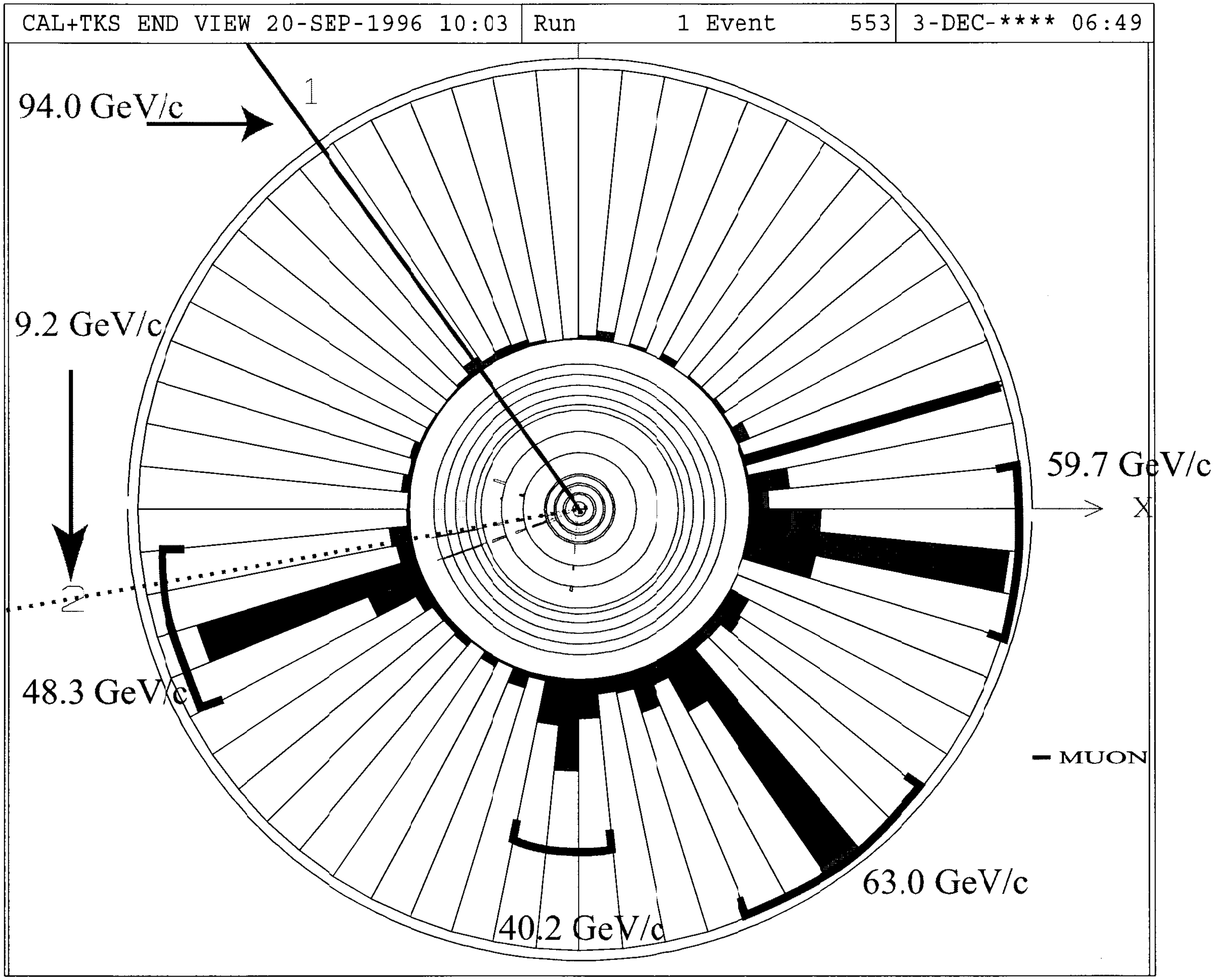
QN06-55

D-Zero Detector at Fermi National Accelerator Laboratory



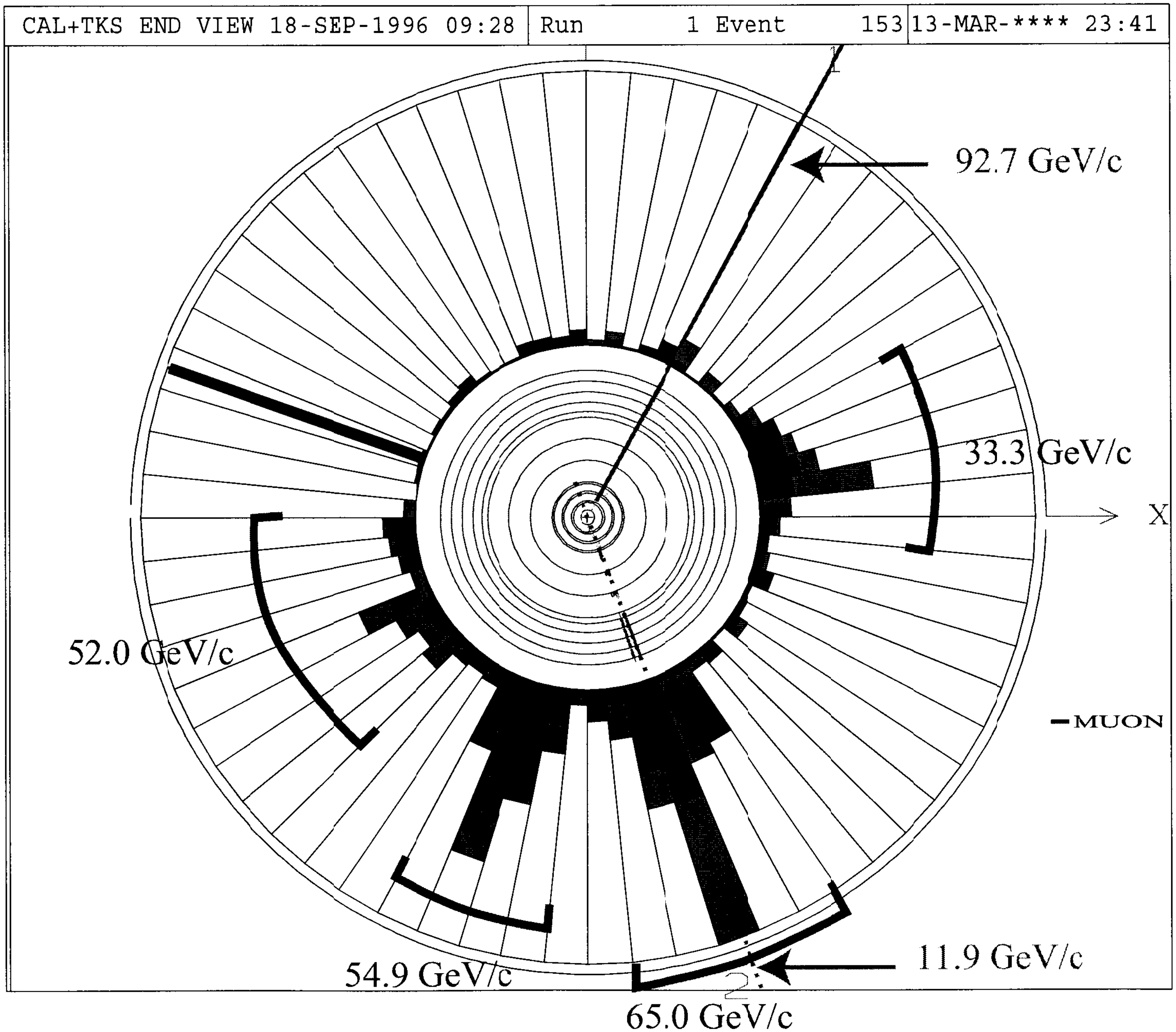
QN06-56

D-Zero Detector at Fermi National Accelerator Laboratory



QN06-57

D-Zero Detector at Fermi National Accelerator Laboratory



QN06-58

Determine the Top Quark Mass

Name:

1. Draw your vector diagram here:

2. Fill in all the momentum values from your color plot in the table below. Add the measured value for the neutrino.

Momentum, Energy or Mass	Jet 1	Jet 2	Jet 3	Jet 4	Muon	Soft Muon	Neutrino

3. Based on your calculations, the mass of the top quark is :

QN06-59

Analyze the Data

The data provided here is a "cleaned-up" version of data taken by Ed Pascuzzi in the summer of 2000. He recorded muon double hits and, using MS Excel, put them into time bins of of width 0.5 microsecond. As muons decay, the number of muons decreases as the time increases. Your job is to take and analyze this data to find the lifetime of the muon using the following steps:

1. Examine the Data Table to begin analysis of the lifetime of the muon. If you have MS Excel, open the spreadsheet muonlife.xls and either analyze the data within that file or transfer to another Excel file for work.
2. Graph the data. (If you use Excel, be sure to make a scatter plot.) How does this compare with your expectation?
3. From your graph, determine the level of background "coincidental double hits" and subtract from the original data.
4. Graph this adjusted data, picking the data range you should graph.
5. Fit to an exponenential $N = N_0 e^{-t/T}$ and find the lifetime T.
6. That's it!

RETURN
to finding the lifetime of the muon

Project Contact: Ken Cecire
Web Maintainer: ed-webmaster@fnal.gov
http://www.jlab.org/~cecire/muonanalysis.html
Last Update: May 23, 2001

QN06-60

Log in

Internet Explorer

http://Quarknet.fnal.gov/grid

Watch the animation
Read Cosmic Ray e-lab page
Log in as guest
Get started
Let's Go—
Read the page that comes up from the "Let's Go"—then click on the bottom of the page on the word "Glossary". Read all terms. Take notes on terms that you think you need to know but might forget.

Back out of the glossary

At the top of the page, click on Resources.

A page will appear with Tutorials, Contacts, Online, Animations will appear.
Under Online, click on Cosmic Extremes and read it all. Take notes.

Go back to page with Tutorials, Contacts, Online, Animations , Under Animations, click on Classroom Cosmic Ray Detector. Click on each part.

Go back to page with Tutorials, Contacts, Online, Animations . Click on and do as many of the Tutorials as possible.

QN06-61

Extra Credit

High energy particle physics games

http://www-ed.fnal.gov/projects/labyrinth/games/

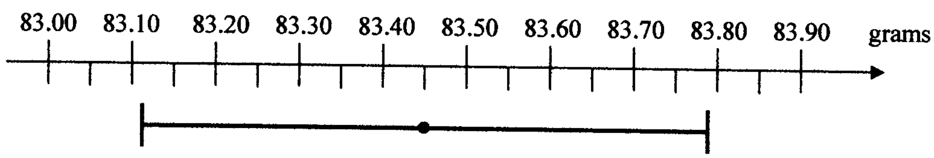
Play the game or games
Find a way to let me know
that you actually played the
game(s)

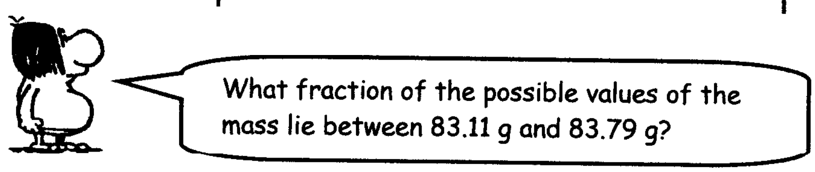
4.2 Coverage probability

Imagine that you are doing an experiment in order to determine the mass of an object. Let us say that as a result of the experiment, you determine that the best approximation of the mass is 83.45 g with a standard uncertainty of 0.34 g.

It is sometimes convenient to write the result as 83.45 ± 0.34 g.

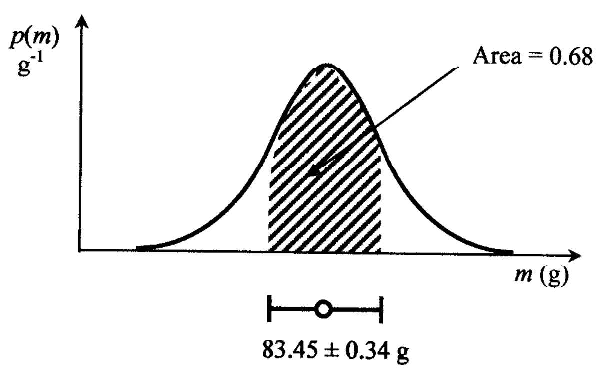
The result 83.45 g ± 0.34 g defines an **interval** on the number line (between 83.11 g and 83.79 g) in which we can expect a (large) fraction of the possible values of the mass to be found. (Remember that we can never know the "true" value of the mass.)





Another way of asking this question is "How confident are you that the value of the mass lies between 83.11 g and 83.79 g ?"

Remember that the standard uncertainty is related to the "average width" of the pdf that you are using (see Appendix G for more details). The area of the pdf within the average width is about 68% of the total area of the pdf. (This is not strictly true, as it does depend of the particular pdf being used, although we don't make a distinction here.)



The shaded area in the pdf above is the area within one standard uncertainty of the best approximation. We call this area, expressed as a percentage, the **coverage probability** (or level of confidence).

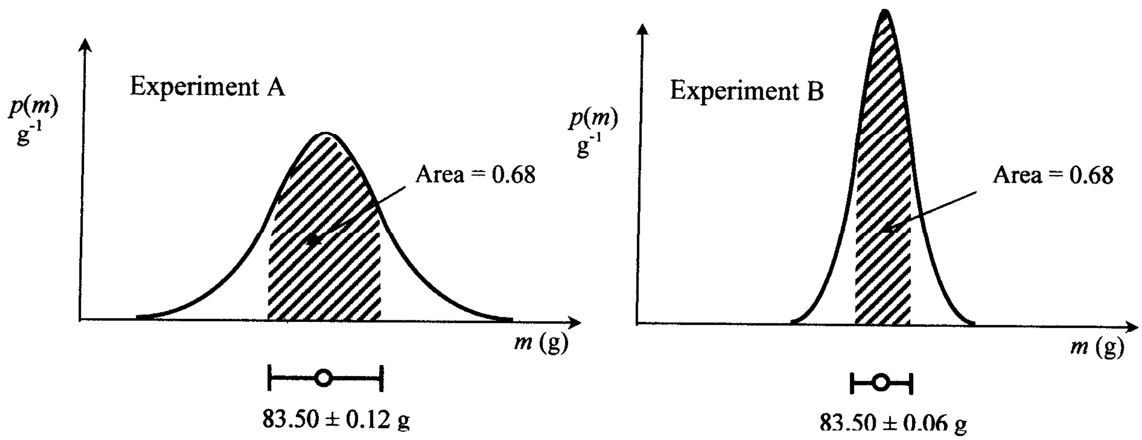
QN06-63

The coverage probability is a measure of the probability that the value of the measurand lies between $y - u$ and $y + u$, where y is the best approximation and u is the standard uncertainty. Remember that you are 100% sure that the value of the measurand lies somewhere under the interval spanned by the entire pdf, since the area under the whole pdf is always unity.

Therefore when you state the result of a measurement as "the best approximation of the mass is 83.45 g with a standard uncertainty of 0.34 g", you understand that **there is a 68% probability that the value of the mass exists somewhere within the interval 83.45 ± 0.34 g, with the most likely value (the best approximation of the measurand) being 83.45 g.**

Remember that there is a 32% probability that the measurand may exist outside of the interval 83.45 ± 0.34 g.

Now consider the two situations below. Two independent experiments were completed in order to determine the mass *m* of an object. The final results of the two experiments are shown below as Gaussian pdf's which are used to describe all available information about the measurand in each case.



From these pdf's it can be seen that both results have 83.50 g for the best approximation of *m*, but measurement A has $u(m)$ = 0.12 g and measurement B has $u(m)$ = 0.06 g.

Which one of the two measurements do you think is the "best" and why?

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<u>Do not</u> proceed to the next page until you have completely answered the questions on this page.

QN06-64

The "best" result is always associated with the measurement with the **smallest uncertainty**. Measurement B has half the standard uncertainty of measurement A. Therefore our 68 % coverage probability is associated with a smaller interval (83.44 g to 83.56 g) for measurement B than measurement A (83.38 g to 83.62 g). In other words we have better knowledge about the value of the measurand from measurement B, since we have the <u>same</u> coverage probability associated with a <u>narrower</u> interval.

4.3 Reporting the result of your measurement

When reporting the result of a measurement, it is better to provide too much information rather than too little. For example, you should describe clearly the methods used to calculate your uncertainties, and present the data analysis in such a way that each of the important steps can be easily followed by the reader of your report.

When reporting the result of a measurement, you should therefore give:
(i) a clear statement of the measurand; and
(ii) the **best approximation** of the measurand and its **standard uncertainty** (remember to give the units).

Sometimes it is also necessary to state the coverage probability (see Appendix H)

For example, the result of the measurement may be reported as:

"...the best approximation of the mass was determined to be 83.45 g with a standard uncertainty of 0.34 g (with a 68% coverage probability, using a Gaussian pdf)."

You can now report your **final results** for the four examples given on the previous pages. Complete the information below. This is how you should always the result of a measurement.

(a) ℓ = __________ ± __________ cm (68 % coverage probability)

(b) f = __________ ± __________ Hz (68 % coverage probability)

(c) V = __________ ± __________ V (68 % coverage probability)

(d) I = __________ ± __________ mA (68 % coverage probability)

4.4 Significant digits

If we determine a particular measurement result (after a series of calculations) to be m = 35.82134 ± 0.061352 kg, how many digits should we quote in our result ?
The uncertainty of 0.0<u>6</u>1352 kg tells us that we are uncertain about the second decimal place in 35.8<u>2</u>134 kg. Our final result is then written as m = 35.821 ± 0.061 kg.

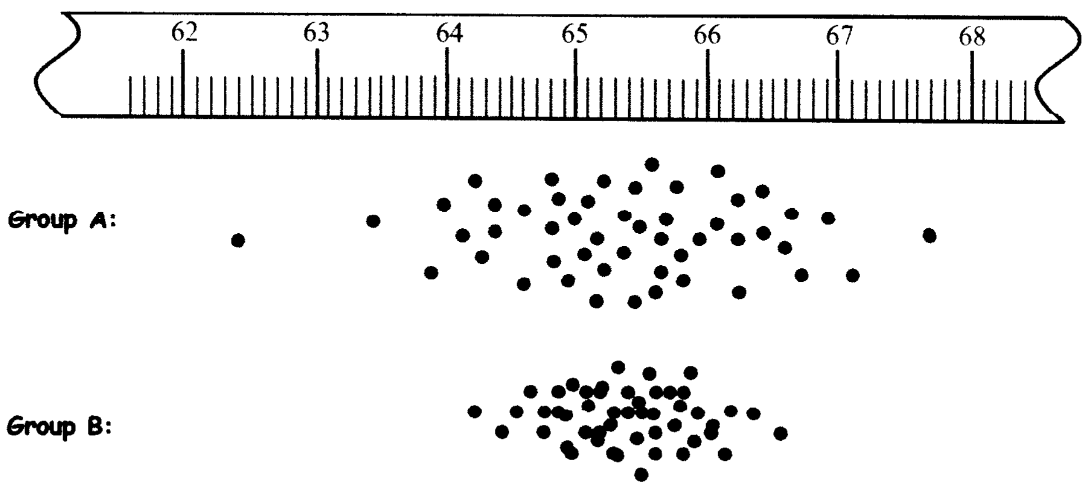
5.2 The Gaussian pdf

For the data $d_1, d_2, \ldots, d_N$, we have seen that the **best approximation** of the value of d is given by the average, or arithmetic mean, $\bar{d}$ of the data:

$$\bar{d} = \frac{1}{N}\sum_{i=1}^{N} d_i$$

where N is the number of readings (in this case 50).

However, is this average value the whole story? What about the spread in the data? For example, compare the two sets of data shown below. The first set (Group A) is the same as discussed above. The second set of data are from another group of students (Group B) who also rolled the ball from the same height, h = 78.0 mm.



What do you notice between the two sets of data ?

____

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Although the average of the two data sets is actually the same (653.6 mm), the data from group A are spread over a larger range than the data from group B. Which group do you think did a more careful experiment? A careful experiment leads to better data. We usually say that the better data are of a higher **quality**. Clearly the quality of the data from Group B is better than the quality of the data of Group A since the spread is smaller in B than for A. We therefore need some way of quantifying the **spread** of $d_1, d_2, \ldots, d_N$ about the mean $\bar{d}$. This spread in the observed readings is a source of uncertainty in our knowledge about d, and you can see that the uncertainty in the measurement of Group B will be smaller than that for Group A.

QNU6-66

We already have the data $d_1, d_2, \ldots, d_{50}$ and so the next step is to use a suitable probability density function which will allow us to model our knowledge about the measurand *d*. When we have a set of readings which show a dispersion, as we have above, it is appropriate to use a **Gaussian** (or "normal") probability density function to depict our knowledge about the measurand.

We can convince ourselves that the Gaussian is a good choice of pdf by thinking about the following. We can group (or "bin") our data by counting how many data readings fall within consecutive intervals of equal width. For the data we are processing, a reasonable "bin" size is 5 mm (see later below why this is the case). Therefore our bins could be 620.0 mm to 624.9 mm, 625.0 mm to 629.9 mm , 630.0 mm to 634.9 mm, etc.

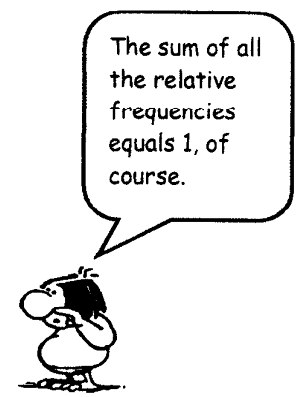
Look carefully at the diagram on the next page to understand what we are doing.

Another way of presenting this analysis of the data is to draw up a **frequency table** (or distribution table). The middle column in Table 5.2 below lists the number of readings falling within each 5 mm - wide bin . We can then calculate the **relative frequency** for each bin, where

$$\text{Relative frequency} = \frac{\text{the number of readings in the bin}}{\text{total number of readings}} = \frac{\text{the number of readings in the bin}}{50}.$$

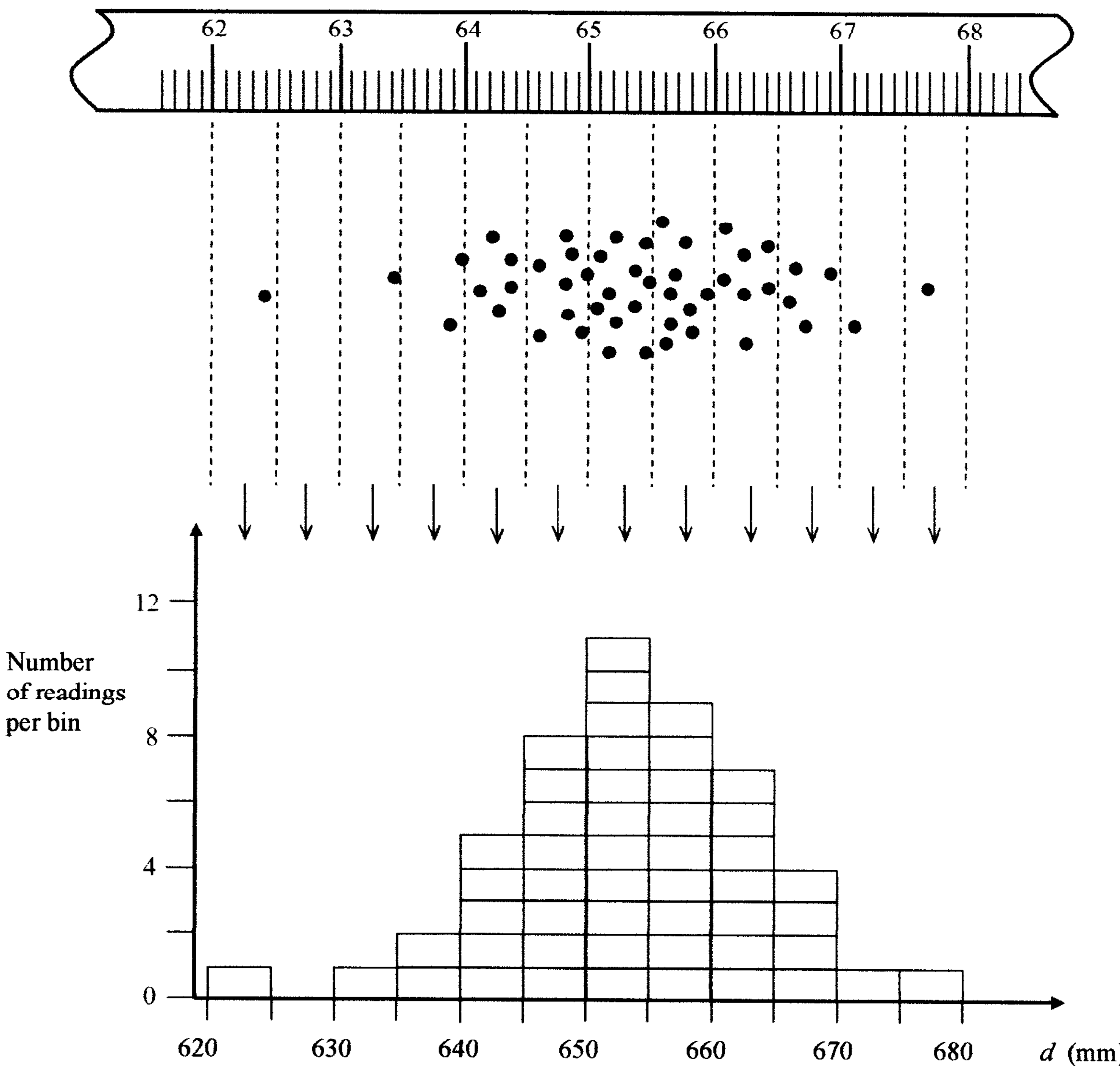
Table 5.2: Frequency table for the data in Table 5.1.

Bin	Number of readings	Relative frequency
620.0 mm to 624.9 mm	1	0.02
625.0 mm to 629.9 mm	0	0.00
630.0 mm to 634.9 mm	1	0.02
635.0 mm to 639.9 mm	2	0.04
640.0 mm to 644.9 mm	5	0.10
645.0 mm to 649.9 mm	8	0.16
650.0 mm to 654.9 mm	11	0.22
655.0 mm to 659.9 mm	9	0.18
660.0 mm to 664.9 mm	7	0.14
665.0 mm to 669.9 mm	4	0.08
670.0 mm to 674.9 mm	1	0.02
675.0 mm to 679.9 mm	1	0.02
	Total: 50	**Total: 1.00**



QN06-67

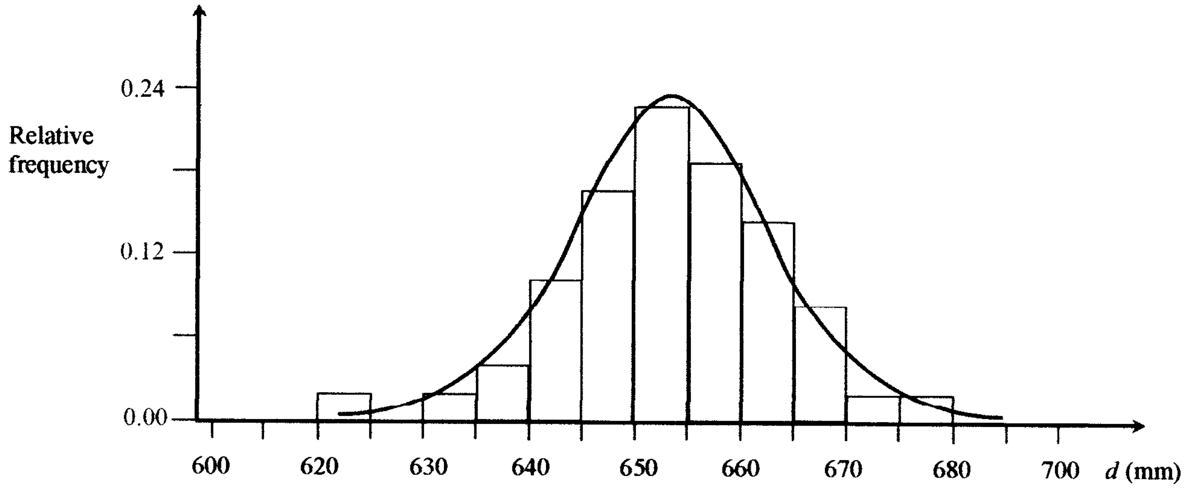
The diagram below illustrates what we are doing. We are counting how many readings (spots on the paper) fall within each 5 mm - wide bin.



We then plot a **histogram** (a vertical bar chart) which illustrates how the data are distributed. You can see that the shape of the histogram looks like a bell-shaped distribution.

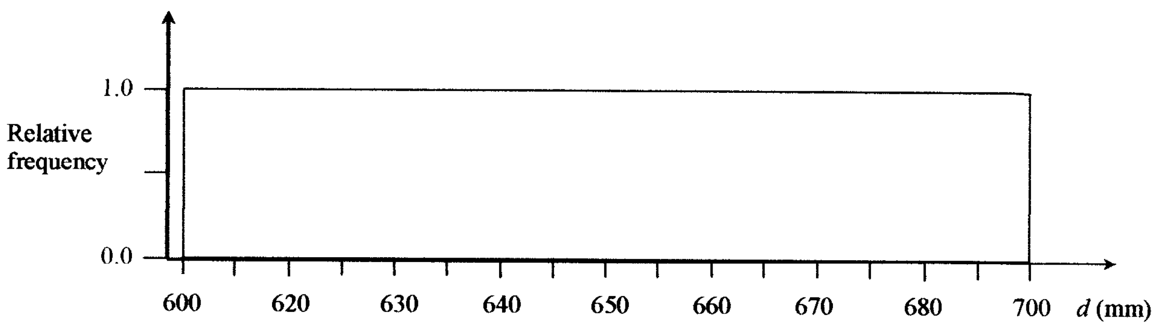
QN06-68

The **relative frequency** tells us the fraction of readings falling within each bin. As we take more and more readings, the histogram of relative frequencies approaches the (theoretical) **probability** of getting a reading between two values of *d*. We can overlap a Gaussian curve on top of the histogram of the relative frequencies from Table 5.2 .The more readings we have and the smaller we make our bin size, the closer the shape of the histogram of relative frequencies will approximate a smooth Gaussian distribution.

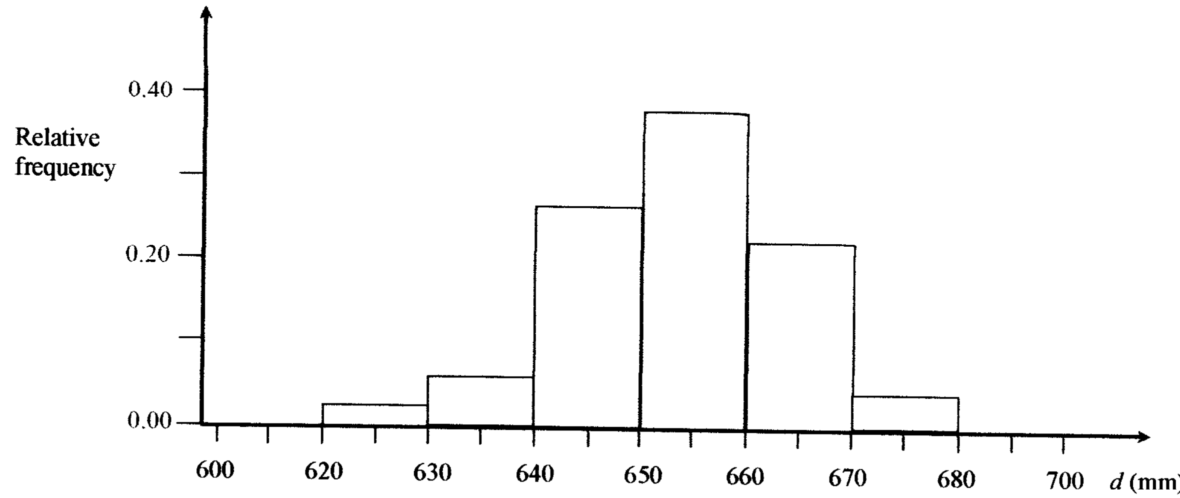


There is nothing mysterious about of choice of bin width (5 mm in this case). We could have chosen a wider or narrower bin width, if we wanted to. However, you need to choose a sensible bin width so that you can see how the data are distributed. To do this you need to look carefully at your data and consider the actual readings, as well as how many readings you have.

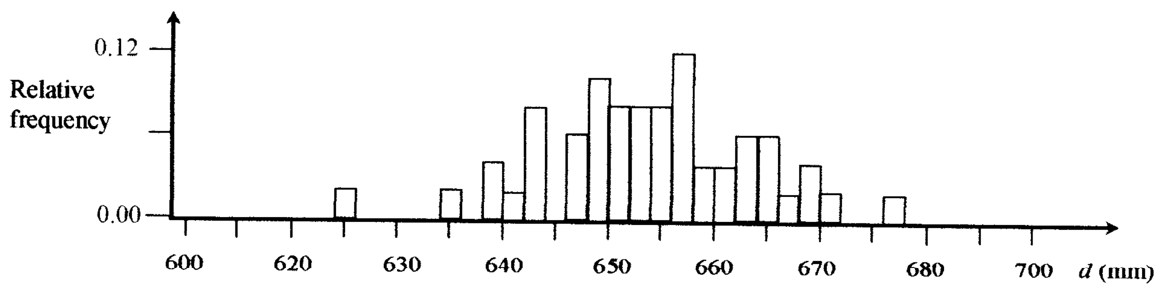
For example, if we had chosen a bin width of 100 mm, then all the data would fall within the same 100 mm-wide bin:



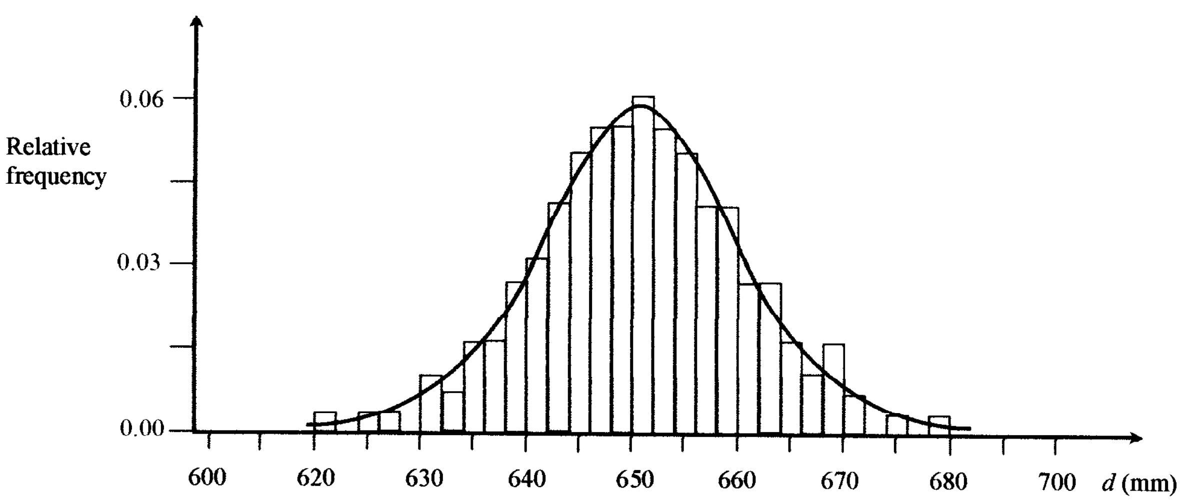
If we had chosen a bin width of 10 mm, then this would have been better. However, although you can start to imagine the shape of a bell-shaped Gaussian distribution, it is not that convincing, since the bins are still too wide.



On the other hand, if we had chosen a bin width of 1 mm, this would also not be good, since we have too <u>few readings</u> to see the shape of the distribution.



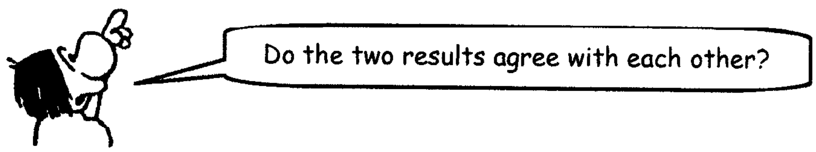
A 1-mm bin width would be fine if we had many more readings. For example, if we had 200 repeated readings instead of 50, then we might see something like the distribution shown below, which again looks like a bell-shaped Gaussian:



QN06-70

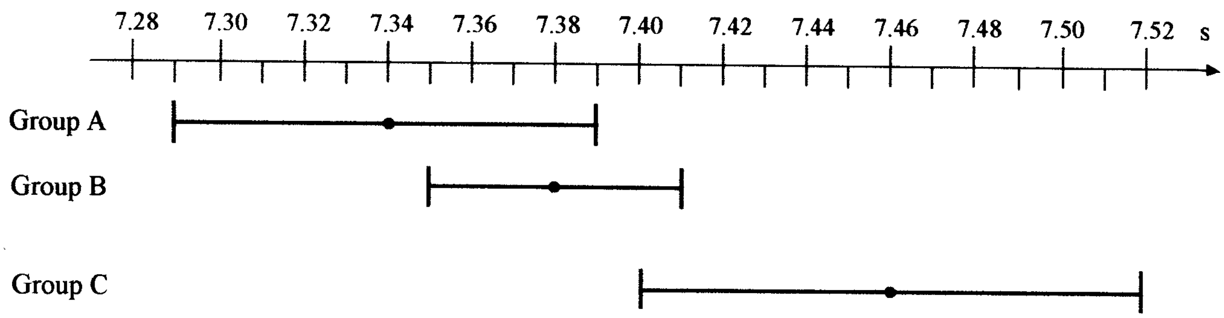
7.2 Comparing different measurements

Consider the following situation. Let us say that one group of scientists (Group A) has measured a time for a particular chemical reaction to be completed to be 7.34 ± 0.05 s where 0.05 s is a standard uncertainty. A second group of scientists (Group B) complete a similar experiment and measure the time for the same chemical reaction to be 7.38 ± 0.03 s.



The answer is quite simple. If the two intervals defined by the two results **overlap**, then the two results agree to within the stated standard uncertainties.

It is easy to understand if you draw the intervals on a number line:



We say that the results of Groups A and B **agree within their stated experimental uncertainties**.

A third group of scientists (Group C) measured the time for the same chemical reaction to be 7.46 ± 0.06 s. You can see that the results of Groups B and C agree within their stated uncertainties, but the results of Groups A and C do not agree with each other.

Which one of the groups (A, B and C) do you think have the best results ?
Explain your answer carefully.

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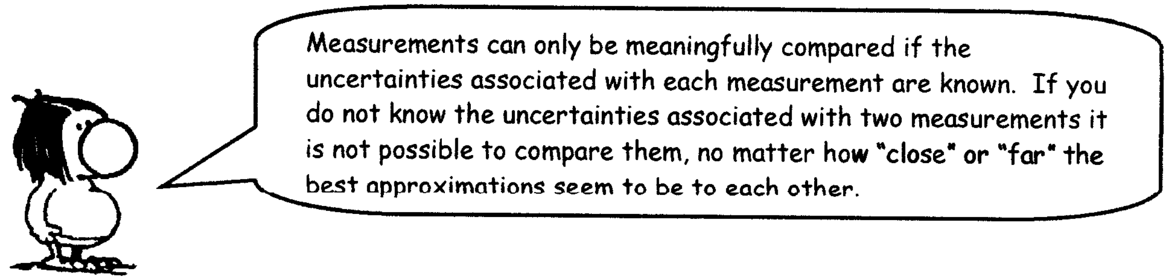
Q N06-71



Now try the following exercise. In each case, decide whether or not the two results (A and B) agree with each other.

	Result A	Result B	Do the two results agree within their experimental uncertainties ? (yes / no)
(a)	4.16 ± 0.04 s	4.16 ± 0.03 s	
(b)	4.16 ± 0.04 s	4.18 ± 0.03 s	
(c)	4.16 ± 0.04 s	4.21 ± 0.03 s	
(d)	4.16 ± 0.04 s	4.23 ± 0.03 s	
(e)	4.16 ± 0.04 s	4.27 ± 0.03 s	
(f)	4.16 ± 0.04 s	4.27 ± 0.04 s	

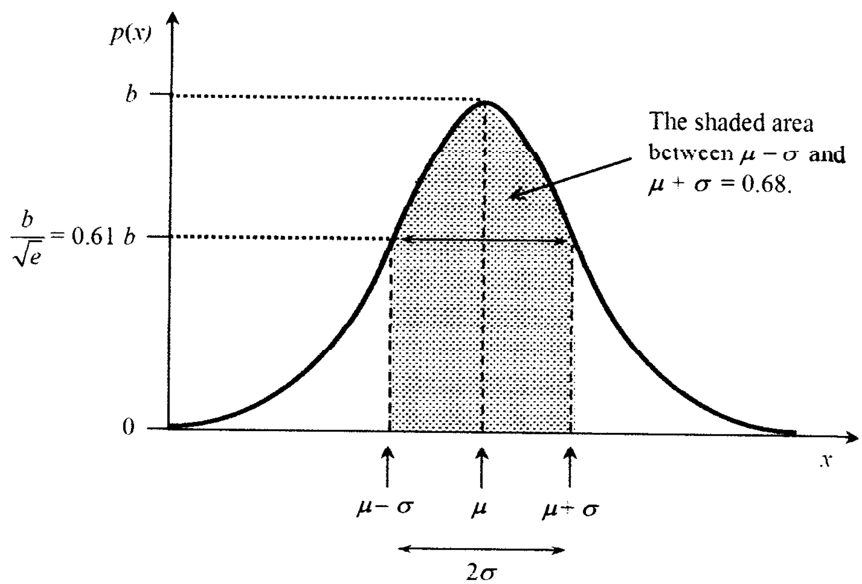
7.3 Repeatability and reproducibility

Repeatability (of results of measurements) has to do with the closeness of the agreement between the results of repeated measurements of the same measurand carried out under the same conditions of measurement. These conditions are called repeatability conditions, which include the same measurement procedure; the same observer; the same measuring instrument used under the same conditions; the same location; and repetition over a short period of time.

Reproducibility (of results of measurements) has to do with the closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions of measurement. A valid statement of reproducibility requires specification of the conditions changed. The changed conditions may include the principle of measurement; the method of measurement; the observer; the measuring instrument; the reference standard; the location; and time.

6.3 The Gaussian pdf

The general equation for a Gaussian pdf is $p(x) = \frac{1}{\sigma\sqrt{2\pi}}\exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right]$. You can see that the Gaussian pdf is described by two parameters, the so-called **expectation value** μ ("μ" = greek symbol "mu", not to be confused with u, the symbol for the standard uncertainty), and the **standard deviation** σ ("σ" = greek symbol "sigma"). The expectation value μ is the value for which the Gaussian pdf is a maximum. The standard deviation σ describes the width of the Gaussian pdf (and is again given by the second moment of the distribution). It turns out that σ may also be determined by considering where the height of the pdf drops to $1/\sqrt{e}$ = 0.61 = 61 % of its maximum value. Half of this width is equal to the standard deviation σ.



If you are using a Gaussian pdf to describe your knowledge about a measurand x based on data that are dispersed randomly about μ, then the best approximation of μ is given by the mean $\bar{x}$, where $\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i$, and the standard uncertainty of $\bar{x}$ (the best approximation of σ), is given by the experimental standard deviation of the mean $s(\bar{x})$, where $s(\bar{x}) = \sqrt{\frac{1}{N(N-1)}\sum_{i=1}^{N}(x_i - \bar{x})^2}$ and N is the number of readings there are in the set.

For the Gaussian distribution the probability that the measurand lies within one standard uncertainty of the best approximation is **68%**.

ONU6-73

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A Laboratory Exercise in Indirect Measurement

Teacher Information

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Here students are to indirectly measure something (the radius of a circle) that they are probably used to measuring directly with a ruler. They are given the sheet with a set of identical circles, a marble and a sheet of carbon paper. By covering the sheet with a random set of dots and finding the ratio of hits inside the circles to marbles thrown, an accurate and suprisingly precise value for the radius of one of the circles can be found. Students could then measure the circles and compare this answer with the answer found directly.

An interesting alternative, if the students are not allowed to ever measure the circles with a ruler, is to have them discuss among groups who has the best results and why. This activity is a nice analog to Rutherford's experiment where he found the size of gold nuclei (circles) by firing alpha particles (marbles) at a thin gold sheet (sheet of paper). Discuss with the students how Rutherford would have confirmed his results. He could not use a ruler to measure directly. He had to rely on the reproducibility of his results by other scientists. A student laboratory information sheet and a master page of circles are available.

This activity takes about one 55-minute period to complete.

Included in the Topics in Modern Physics, May 1990, and Catching the Sun, 1992, Fermilab.

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GNOC-74

Adult groups, families, scouts and more, join our Prairie Quadrat Study.

A Laboratory Exercise in Indirect Measurement

Discussion: Modern physics depends heavily on indirectly determining physical properties of objects. The following activity may help convince students that indirect determinations are important methods of obtaining accurate information. This exercise can be used as an introduction to a discussion of the Rutherford model of the atom. This activity simulates an experiment in particle physics where a target material would be bombarded by high speed particles, and the collisions studied. It gives you a chance to use a "Monte Carlo" technique.

Problem: Indirectly determine the radius of a single target circle.

Use copies of the circle sets on the following pages. Place the circled paper on the floor, face down over a sheet of carbon paper. Working in pairs drop marbles or ball bearings from head height so that they hit the paper. The sphere must be caught after the first bounce. Repeat this at least 100 times. It may be more convenient to drop the marbles from just above the paper, however, one should then take care to distribute the hits as randomly as possible over the entire target area. It is "OK" to miss the paper from time to time. Those points will naturally be excluded form the data set. (Note the paper is 21.5 cm by 28.0 cm.)

Analysis: Count the total number of dots on the paper (total hits), as well as the number of dots just completely within a circle (circle hits). Determine the total area of the paper, and count the total number of circles on the paper. If the circles are of uniform size and the hits are randomly distributed, then one can assume:

(circle hits)/(hits) = (area of all circles)/(rectangular area)

Therefore, you can calculate the total area of all circles. From this you can calculate:

area of one circle = (area of all the circles)/(number of circles)

The area of one circle can be used to calculate the radius of a circle (area = pi*radius*radius). This calculated radius may then be compared with a direct radius measurement.

Questions:

1. What is the radius of one circle?

2. How does the indirect measurement (using the marbles) compare to a direct measurement (such as using a ruler)?

Included in the Topics in Modern Physics, May 1990, and Catching the Sun, 1992, Fermilab.

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QN06-75

Students' understanding of measurement and uncertainty

Saalih Allie and Andy Buffler (UCT)
Fred Lubben and Bob Campbell (University of York, UK)

M.Sc. Student: Trevor Volkwyn

Over the past few years we have researched first year physics students' understanding of the nature of measurement (see Allie et al., 1998; Lubben et al., 2001; Buffler et al., 2001). We have developed a number of research tools for this purpose, some of which are included as the "Physics Measurement Questionnaire" below. A model of student thinking about dispersion in data has been developed which has been termed "point" and "set" paradigms. The point paradigm is characterized by the notion that each measurement could in principle be the true value. As a consequence each measurement is regarded as independent of the others and the individual measurements are not combined in any way. It also follows that a measurement is perceived as leading to a single, 'point-like' value rather than establishing an interval. In its most extreme form, this way of thinking manifests itself in the belief that only one single measurement is required to establish the true value. If a series of measurements is taken, subsequent decisions are based on the individual data points only, such as for example, the selection of a recurring value in a data set or a one-to-one comparison of data values between different data-sets. The set paradigm is characterised by the notion that each measurement is only an approximation to the true value and that the deviation from the true value is random. As a consequence, a number of measurements are required to form a distribution that clusters around some particular value. The best information regarding the value is obtained by combining the measurements using theoretical constructs in order to describe the data collectively. The operational tools that are available for this purpose include the formal mathematical procedures that can be used to characterise the set as a whole, such as the mean and the standard deviation. In turn, both the mean and the standard deviation become tools for making comparisons with other data-sets or with theory. We have found that the majority of science students who arrive at the University of Cape Town (UCT) operate almost completely within the "point paradigm", and that even

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after a carefully structured laboratory course (Allie and Buffler, 1998) most students had not shifted completely to "set" paradigm thinking.

Download the Physics Measurement Questionnaire:

- Instructions
- The PMQ probes

The problem with the "traditional" laboratory course

Although one of the most important aspects of putting together a teaching sequence is bringing together the philosophy, logic and modes of thinking that underlie a particular knowledge domain, introductory measurement in physics is usually taught as a combination of apparently rigorous mathematical computations and vague rules of thumb. We believe that this is a consequence of the logical inconsistencies in traditional data analysis, which is based on the frequency interpretation of probability. This approach, often called "frequentist", is the one used or implied in most introductory laboratory courses. For example, in the frequentist approach, "errors" are usually introduced as a product of the limited capability of measuring instruments, or in the case of repeated measurements, as a consequence of the inherent randomness of the measurement process and the limited predictive power of statistical methods. These two different sources of "errors" cannot be easily reconciled, thus creating a gap between the treatment of a single reading and of ensembles of dispersed data. For example, the theory applicable to calculating a mean and a standard deviation is premised on the assumption of a large number or readings (20+). Yet, when students perform an experiment in the laboratory they often take 5 or fewer readings. Furthermore, there is no logical way to model statistically a single measurement within this approach. We have therefore concluded that the logical inconsistencies in the traditional approach to data treatment, together with the form of instruction that ignores students' prior views about measurement, further cultivate students' misconceptions about measurement in the scientific context.

A probabilistic interpretation of measurement

The need for a consistent international language for evaluating and communicating measurement results prompted (in 1993) the ISO (International Organization for Standardization) to publish recommendations for reporting measurements and uncertainties based on the probabilistic interpretation of measurement. All international standards bodies, including the UIPAP (International Union of Pure and Applied Physics) and UIPAC (International Union of Pure and Applied Chemistry), have adopted these recommendations for reporting scientific measurements. A number of documents currently serve as international reference standards. The most widely known are the so-called International Vocabulary of Basic and General Terms in Metrology (ISO, 1993) and the Guide to the Expression of Uncertainty in Measurement (ISO, 1995).

The recommended approach (ISO 1993, 1995) to metrology is based on the use of probability theory and the concept of the probability density function for the analysis and interpretation of data. A key element of the ISO guidelines is how it views the measurement process. The guidelines state that "In general, the result of a measurement is only an approximation or estimate of the value of the specific quantity subject to measurement, that is, the measurand, and thus the result is complete only when accompanied by a quantitative statement of its uncertainty." Uncertainty itself is defined as "a parameter associated with a measurement result, that characterizes the dispersion of the values that could reasonably be attributed to the measurand" (ISO 1993, 1995).
At the beginning of the measurement process, new data are combined with all prior information about the measurand (the quantity being measured) to form an updated state of knowledge from which inferences

about the measurand are made. The formal mathematics used to allow these inferences are probability density functions (pdfs) with the (true) value of the measurand as the independent variable. (We note that there is no difference between the terms "the value of the measurand" and "the true value of the measurand"). Thus, the measurement process includes using a pdf which best represents our knowledge about the measurand. We emphasize that both the case of the single reading and the case of a set of repeated readings with dispersion, involve seeking the pdf for the measurand. The last step in the measurement process involves making inferences about the measurand based on the (final) pdf.

Although the ISO recommendations do not refer explicitly to the underlying philosophy, the formalism relies on the Bayesian approach to data analysis.. The final pdf is usually characterized in terms of its location, an interval along which the (true) value of the measurand may lie, and the probability that the value of the measurand lies on that interval. In metrological terms these are, respectively, the best estimate of the measurand and its uncertainty, and the confidence level (the percentage area under the pdf defined by the uncertainty interval). Typical statements describing a measurement result are of the form "the best estimate of the value of the physical quantity is X with a standard uncertainty U and the level of confidence we have that the measurand lies on the interval X ± U is Z %". In this approach, instrument readings are considered as constants, while the concept of probability is applied to any claims made about the value of the measurand which is considered a random variable. Neither the measurand itself nor the data "possess" either uncertainty or probability, but these concepts are applicable to the inferences that are made. This contrasts with the traditional approach, where expressions are used like "the error of the measurement" or "the uncertainty of the instrument scale".

The new laboratory course
We have designed a new curriculum for the first year physics laboratory which deals with the concepts that are central to the understanding of measurement and uncertainty in a way that recognises the understandings that students bring to their university studies. The materials attempt to weave together our desire for student understanding of measurement and uncertainty, our expectations of the role of the laboratory course and the nature and philosophy of experimentation as described by the ISO recommendations (ISO 1993, 1995). An interactive student workbook has been written which aims to introduce the main ideas of measurement and uncertainty. Students work through the activities in the workbook in small groups in a tutorial-type environment and are assisted when necessary by one of a number of roving tutors. On alternate weeks, the students are engaged in activities in the laboratory which are designed to support the new ideas about measurements and provide "hands-on" laboratory experiences. At the same time, reporting on a completed experiment also forms a central part of the experience and producing writing intensive reports serves to underlie the laboratory course (see Allie et al., 1997). In general the laboratory tasks are framed in the form of problems that require an experimental investigation for their resolution and have to be reported on to a particular audience. The course consists a 3 hour session per week for 16 weeks and was piloted with a class of 160 "Science Foundation Programme" (Allie and Buffler, 1998) students in the Physics Department at the University of Cape Town in 2002 and 2003.

Outline of the content of the interactive student workbook.
Unit 1. Introduction to measurement The relationship between science and experiment. Designing an experiment. Tables and graphs. The laboratory report.
Unit 2. Basic concepts of measurement Probability and inference. Reading digital and analogue scales. The nature of uncertainty. A probabilistic model of measurement.
Unit 3. The single measurement Probability density functions. Representing knowledge graphically using a pdf. Evaluating standard uncertainties for a single reading. The result of a measurement.
Unit 4. The repeated measurement Dispersion in data sets. Evaluating standard uncertainties for multiple readings. Type A and type B evaluation of uncertainties.

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Unit 5. Working with uncertainties Propagation of uncertainties. Combined standard uncertainty. The uncertainty budget. Comparing different results. Repeatability and reproducibility
Unit 6. Modelling trends in data Principle of least squares. Least squares fitting of straight lines.

Download the new workbook:

Introduction to Measurement in the Physics Laboratory: A Probabilistic Approach

Please let us know if you make use of this book in a teaching context and especially before you decide to mass produce it.

Evaluation of the new course
The evaluation of the new course involved the diagnostic testing of the students both before and after the course as well as a number of interviews with individual students. The interviews are considered in a companion paper in these proceedings (Lubben et al., 2003). The written research instrument comprised a set of nine written probes (questionnaires) based on those developed for a previous study (Buffler et al., 2001), but modified for the new course materials. The probes focused on decisions to be made while collecting data, the procedural decisions used for data processing and the reasoning used by students when comparing two sets of measurements of the same quantity. The form and style of the probes are described in detail in Buffler et al. (2001). Briefly, each probe presented a situation where a decision was required, while offering a number of alternative suggested actions. All the probes referred to different aspects of the same posited experiment and were answered individually in strict sequence under formal examination-type conditions. The analysis of the probes consisted of categorizing the student responses according to the answer choice together with the different types of reasoning evidenced. The coding of the responses was undertaken using an alphanumeric scheme which was developed and tested previously (Allie et al., 1998). This enabled the underlying paradigm, i.e. point or set, to be identified for each student.

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