Physics 125: Elementary Particle Physics

Syllabus
Spring 2008

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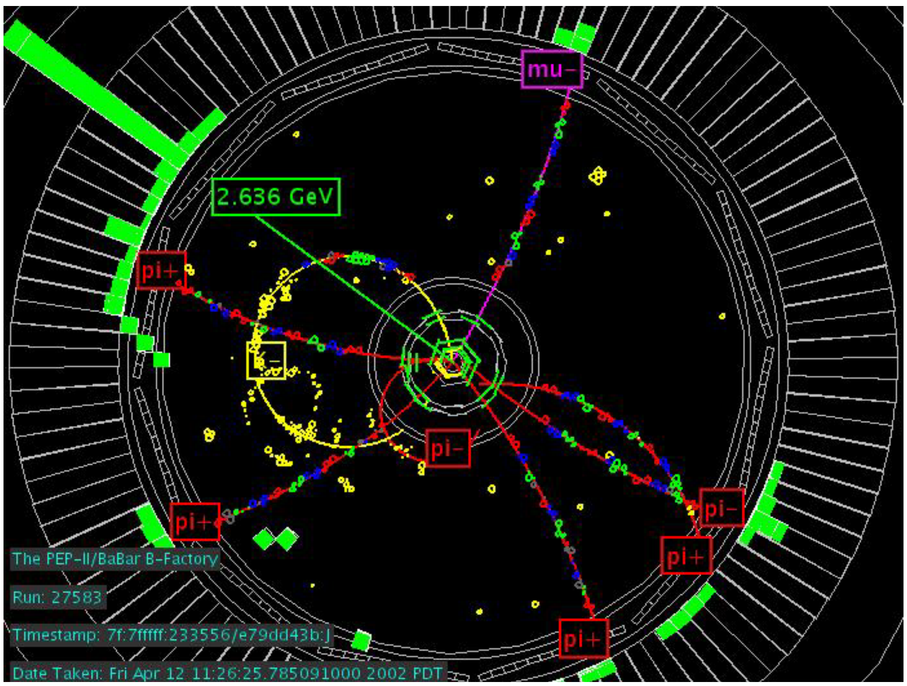


Particles resulting from the collision of an electron (e^-) and a positron (e^+) at the PEP-II storage ring. The horizonal distance scale across the picture is approximately 2.5 m.

What is particle physics?

Particle physics addresses fundamental and challenging questions. What are the fundamental constituents of matter? How do they interact? What are the laws of physics that governed the behavior of matter in the early evolution of the universe?

The smallest objects observed so far—quarks, leptons, and gauge bosons—behave in a manner that we can now describe in great detail. Yet, in spite of tremendous progress in this field, many deep mysteries remain. What is the origin of mass? What is the nature of the dark matter inferred from astrophysical observations? Why do neutrinos have very tiny masses? Why is there a three-fold replication of a basic set of particles (the generation puzzle)? Are quarks truly elementary particles? Why are some conservation laws violated by a narrow class of processes? Why is there much more matter than antimatter in the universe? Is there, as theorists predict, an undiscovered ``supersymmetric'' partner for every known type of elementary particle? Are there additional undiscovered dimensions of space?

To make progress in the study of elementary particles, one needs sophisticated experimental and theoretical tools. We use accelerators of monumental size to produce particle collisions at energies that are equal to those 10^{-12} s after the big bang. We routinely collide matter with antimatter, destroying the initial particles and creating new ones. The detectors that we use to study these collisions are nearly as impressive. Here at UCSB, the high-energy physics group is very active in constructing such detectors and in analyzing the results of experiments that we perform at various accelerator laboratories.

The theoretical tools required to analyze elementary particle phenomena are also extremely interesting and challenging. Nearly all processes involve phenomena that must be described with relativistic quantum mechanics. Theories must also cope with the fact that, in high-energy collisions, particles are usually created or destroyed. In other words, we don't simply smash two watches together and observe the little pieces come flying out---entirely new pieces are created! We have come to understand that the "new" particles observed in such experiments are every bit as fundamental and important to piecing together the puzzle of matter as the particles that make up atoms. The theoretical framework for describing these processes is called quantum field theory.

In Physics 125 we will make a start towards understanding the nature of elementary particles and their interactions. We can go quite far without using the full apparatus ofquantum field theory. We will, however, need to use special relativity and quantum mechanics routinely.

Finally, let me repeat a sentiment of a physicist I know. She said that doing particle physics is like climbing a mountain: the journey up can be a struggle, but the view from the top is great!

How to succeed in this course

You will face four main challenges in this course:

1. Unlike upper division courses in some other subjects like electromagnetism or classical mechanics, you probably have not seen this material before in a simpler form. There is a large amount of ideas, knowledge, and terminology that you must learn in a very short time.
2. The course will make substantial use of quantum mechanics.
3. The course will make substantial use of special relativity.
4. The pace will be fast. If you do not keep up with the reading, HW, and absorbing the lectures, you will get lost very quickly.

If you have not encountered quantum mechanics and special relativity before, this course is probably not a good use of your time right now. If you have had these subjects before, Physics 125 will help you understand them better by applying them to interesting situations.

Here is some advice on how to deal with this challenging subject.

1. **Keep up with the reading and do the homework on time.** Take careful notes when you read the textbook and bring lots of questions to class. Come to office hours to get mysterious concepts clarified! Do not wait to start the homework assignments until the night before they are due. When an assignment is handed out, read it as soon as possible. You might then notice that some of the questions are at least partially answered in the lectures, or you might realize that you need to get started especially early if some computer resources are needed.
2. **Ask questions!** Some students are too intimidated to ask questions. Questions don't need to be brilliant. Here is a perfectly good one: "Could you please explain the main point again?" Remember that your professor cannot anticipate all of the particular issues that will confuse you, so you should ask questions in class and office hours. Office hours are especially valuable in clearing up misunderstandings because there is more time.
3. **Remember information**. In this course, there will be more to remember than you are probably used to. This is because we are studying real, crucial physical systems, not just getting practice in applying laws of physics to a variety of situations. In fact, this type of learning is closer to actual research, where you have to know where the boundary is between the known and the unknown in order to identify the most fruitful avenues of investigation. (The first person in the class to inform me that she/he has read this will get a reward.) And knowing the properties of real physical systems is critical for understanding what methods can be used to make new discoveries.
4. **Remember the main results of homework problems: you will often need to use them later.** Many of the problems will address important issues and will be applied in many different contexts; they are not simply cooked-up examples. The

attitude, "I can always just look it up in the book" leads to an inability to reason about new situations.

5. **Recognize that this is a very difficult subject. You need to make a proportional level of effort to succeed.** You may well want to consult additional textbooks or resources on the web. I can make many suggestions if you are interested in going deeper.

Grades, homework, tests, and all that stuff

- **Immediate action item: please order a copy of the "Particle Physics Booklet (320 pages)** 2006 edition" from http://pdg.lbl.gov/2007/html/receive_our_products.html. This is a small pocket edition. You do not need to order the 1200 page book.
- Homework will be assigned on Wednesday and will be due on class on the following Wednesday.
- Graduate Teaching Assistant: Chris Justus
- Lectures: M, W, F 12:00—12:50 in Girvetz 2123
- Professor Richman's office hours: tentatively, Tues 11:00 AM-noon and Thurs 3:00-5:00 PM or by appointment.
- Lunchtime physics policy: if you ask a couple days in advance, I will try to be available to discuss particle physics over lunch with a group of at least three students. (Due to time constraints, we'll need to eat on campus.)
- E-mail policy: I sometimes get 100 e-mails per day. It is very difficult to keep up with all of it. For any e-mail that you send, please include a subject line "Physics 125". In general, it's better to talk to me about something rather than sending an e-mail.
- Grading policy:
  1. Homework: 30%
  2. Midterm: 20%
  3. Final exam: 50%
- Textbook: *Introduction to Elementary Particles,* by David Griffiths
- Final Exam Date: see schedule below.

Schedule for Physics 125 in Spring 2008

Class	Date	Topics	Chapters in Griffiths
1	Mon, Mar 31	Goals of particle physics; definitions and characteristics of elem. particles	Introduction, C1 (History)
2	Weds, Apr 2	Units, constants, and energy scales	finish C1
3	Fri, Apr 4	Particle processes; particles and fields; gauge bosons, quarks, leptons, & hadrons	C2
4	Mon, Apr 7	The four forces; particle content of the Standard Model; properties of quarks and hadrons	C2

5	Weds, Apr 9	Interactions, fundamental vertices, Feynman diagrams (I)	C2
6	Fri, Apr 11	Interactions, fundamental vertices, Feynman diagrams (II)	C2
7	Mon, Apr 14	Feynman diagrams; hierarchy of interactions; examples (III)	C3
8	Weds, Apr 16	Special relativity; Lorentz transformation; 4-vectors & invariants	C3
9	Fri, Apr 18	Applications of relativity; decay and scattering processes, Klein-Gordon wave equation	C3
10	Mon, Apr 21	Symmetries and Conservation Laws	Notes and parts of C4
11	Weds, Apr 23	Particle detectors (I)	Notes
12	Fri, Apr 25	Particle detectors (II)	Notes
13	Mon, Apr 28	Calculating decays rates & cross sections: concepts	C6
14	Weds, Apr 30	Exponential decay law and Breit-Wigner line shape	C6
15	Fri, May 2	Feynman rules & phase space (I)	C6
16	Mon, May 5	Feynman rules & phase space (II)	C6
17	Weds, May 7	Feynman rules & phase space (III)	C6
18	**Fri, May 9**	**MIDTERM**	**C1—4; Lecs 1-12**
19	Mon, May 12	Applications of Feynman Rules (I) Physics of the propagator; s- and t-channel scattering; Rutherford scattering angular dependence; muon decay; origin of Fermi's constant	C6
20	Weds, May 14	Applications of Feynman rules (II)	C6
21	Fri, May 16	Applications of Feynman rules (III)	C6
22	Mon, May 19	Weak decays; Cabibbo-Kobayashi-Maskawa (CKM) matrix of quark couplings to the W boson	Notes
23	Weds, May 21	Neutrinos (I): scattering; cross sections and interactions lengths; weak neutral currents	Notes
24	Fri, May 23	Neutrinos (II): oscillations	Notes
-	Mon, May 26	Memorial Day Holiday	
25	Weds, May 28	Neutrinos (III): oscillations, continued	Notes
26	Fri, May 30	LHC Physics (I): Gauge bosons, Higgs Particles, and Supersymmetry	Notes
27	Mon, June 2	LHC Physics (II)	Notes
28	Weds, June 4	LHC Physics (III)	Notes
29	Fri, June 6	LHC Physics (IV)	Notes
FINAL	**Tues, Jun 10**	**FINAL EXAM noon—3:00 PM; see**	**Covers textbook, HW, lectures**

The tables on the following pages are available at

http://pdg.lbl.gov/2007/html/outreach.html

Please study this information carefully.

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model is a quantum theory that summarizes our current knowledge of the physics of fundamental particles and fundamental interactions (interactions are manifested by forces and by decay rates of unstable particles).

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

*See the neutrino paragraph below.

Spin is the intrinsic angular momentum of particles. Spin is given in units of $\hbar$, which is the quantum unit of angular momentum where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $=1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$) where 1 GeV = 10^9 eV $=1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.

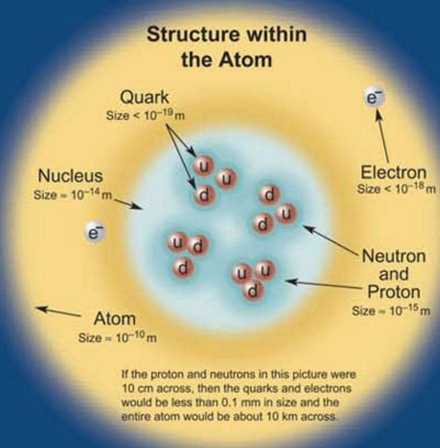
Neutrinos

Neutrinos are produced in the sun, supernovae, reactors, accelerator collisions, and many other processes. Any produced neutrino can be described as one of three neutrino flavor states ν_e, ν_μ, or ν_τ, labelled by the type of charged lepton associated with its production. Each is a defined quantum mixture of the three definite mass neutrinos ν_L, ν_M, and ν_H for which currently allowed mass ranges are shown in the table. Further exploration of the properties of neutrinos may yield powerful clues to puzzles about matter and antimatter and the evolution of stars and galaxy structures.

Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$ but not $K^0 = d\bar{s}$) are their own antiparticles.

Structure within the Atom



BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ (W bosons)	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Only quarks and gluons carry "strong charge" (also called "color charge") and can have strong interactions. Each quark carries three types of color charge. These charges have nothing to do with the colors of visible light. Just as electrically-charged particles interact by exchanging photons, in strong interactions, color-charged particles interact by exchanging gluons.

Quarks Confined in Mesons and Baryons

Quarks and gluons cannot be isolated – they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs. The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge.

Two types of hadrons have been observed in nature **mesons** $q\bar{q}$ and **baryons** qqq. Among the many types of baryons observed are the proton (uud), antiproton ($\bar{u}\bar{u}\bar{d}$), neutron (udd), lambda Λ (uds), and omega Ω^- (sss). Quark charges add in such a way as to make the proton have charge 1 and the neutron charge 0. Among the many types of mesons are the pion π^+ ($u\bar{d}$), kaon K^- ($s\bar{u}$), B^0 ($d\bar{b}$), and η_c ($c\bar{c}$). Their charges are +1, –1, 0, 0 respectively.

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction (Electroweak)	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

Visit the award-winning web feature *The Particle Adventure* at

ParticleAdventure.org

This chart has been made possible by the generous support of:
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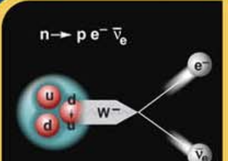
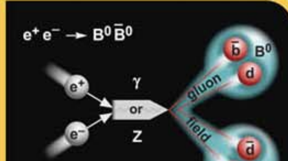
Particle Processes

These diagrams are an artist's conception. Blue-green shaded areas represent the cloud of gluons.



A free neutron (udd) decays to a proton (uud), an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β (beta) decay.



An electron and positron (antielectron) colliding at high energy can annihilate to produce $\bar{B}^0$ and B^0 mesons via a virtual Z boson or a virtual photon.

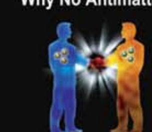
Unsolved Mysteries

Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, mini-black holes, and/or evidence of string theory.

Universe Accelerating?

The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?

Why No Antimatter?



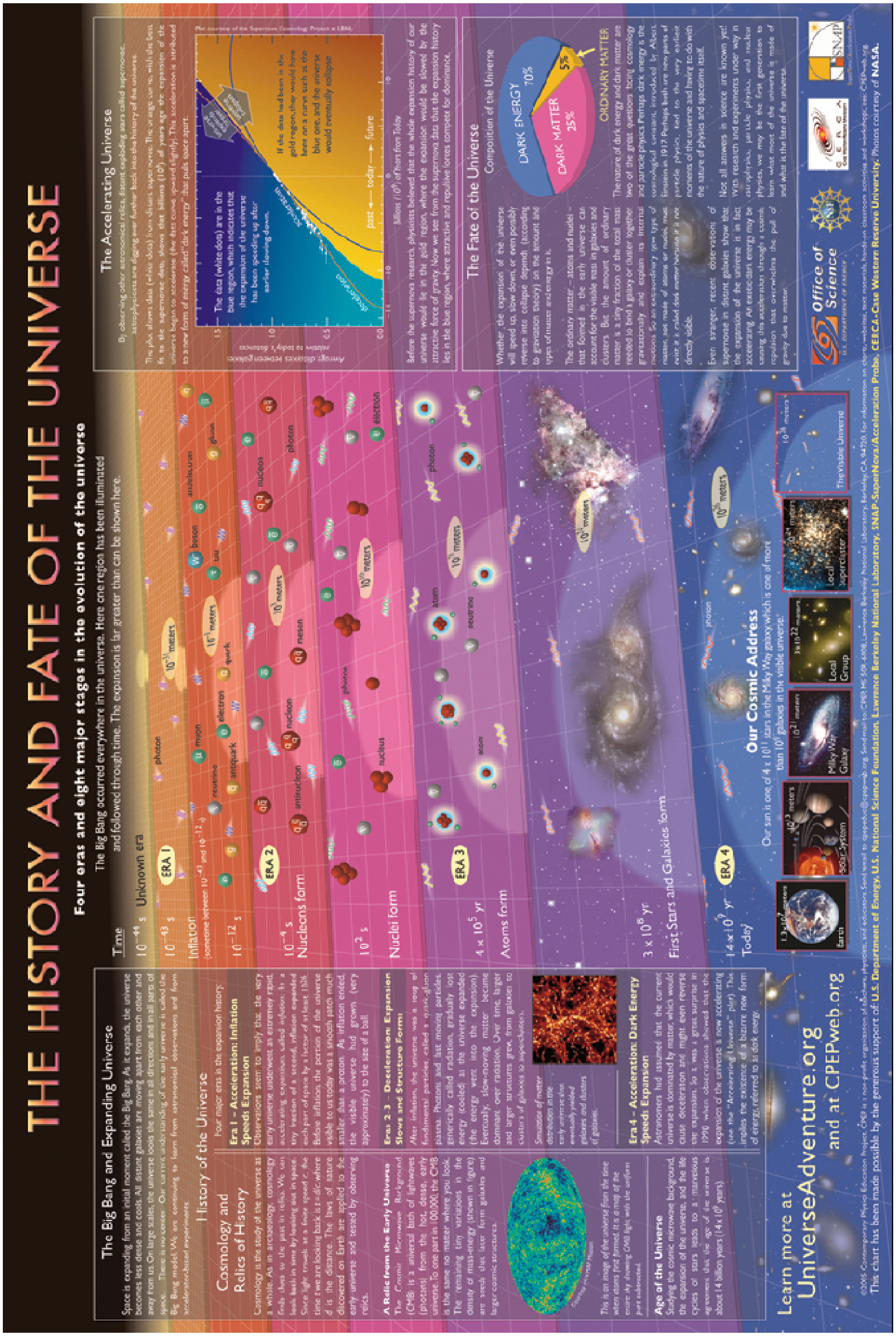
Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?

Dark Matter?

Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does this dark matter consist of new types of particles that interact very weakly with ordinary matter?

Origin of Mass?

In the Standard Model, for fundamental particles to have masses, there must exist a particle called the Higgs boson. Will it be discovered soon? Is supersymmetry theory correct in predicting more than one type of Higgs?


THE HISTORY AND FATE OF THE UNIVERSE
Four eras and eight major stages in the evolution of the universe
The Big Bang occurred everywhere in the universe. Here one region has been illuminated and followed through time. The expansion is far greater than can be shown here.
The Big Bang and Expanding Universe
Cosmology and Relics of History
History of the Universe
Time
Unknown era
ERA 1
Inflation
ERA 2
Nucleons form
Nuclei form
ERA 3
Atoms form
First Stars and Galaxies form
ERA 4
Today
Our Cosmic Address
The Accelerating Universe
The Fate of the Universe
Composition of the Universe
DARK ENERGY 70%
DARK MATTER 25%
5%
ORDINARY MATTER
Office of Science
Learn more at
UniverseAdventure.org
and at CPEPweb.org