Science of the Physical Universe 22:
The Unity of Science: From the Big Bang to the Brontosaurus[1] and Beyond

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General-Education Requirements Satisfied:

This course, when taken for a letter grade, meets the General Education requirement for either Science of the Physical Universe or Science of Living Systems, but not both.

Goals:

A main goal of the course is to demonstrate through examples the importance of asking fundamental questions, especially in spawning major advances in science.

We also intend to impart an appreciation for the power of the methods of science, and to foster a mastery of some of the basic knowledge obtained by humans' uncovering of Nature's secrets.

Course Summary:

Science is like a well-woven, ever-expanding fabric, designed to uncover Nature's secrets. This course emphasizes the strong connections between subfields of science, showing it as the never-ending and greatest detective story ever told, with evidence always the arbiter. These characteristics are exhibited in the semi-historical treatment of three main themes: unveiling the universe, the earth and its fossils, and the story of life.

A more detailed description of the course is on pages 5 -11.

Prerequisites:

Although no knowledge of advanced math (e.g., calculus) or prior knowledge of science is needed, some elementary algebra, plane geometry, and very basic trigonometry, as well

[1] Resurrected for poetic purposes. ("Brontosaurus" had been eased out of the taxonomic pantheon by "Apatosaurus," but now seems to have made a comeback!)

as scientific notation, will be used in the course. Refresher sessions and individual tutoring, specifically for this math, will be available to any students who would like to have such reviews.

Readings:

All literature to be used will be available on the course website, so students need not purchase any material. Reading assignments will mostly be taken directly from the published, professional literature with care taken in trying to avoid jargon-laden articles, which are nearly impenetrable for lay persons. Older literature is far more accessible to non-experts and will constitute the majority of the assignments; the rest may come mainly from secondary sources. Reading assignments will generally be posted on the course website on the Wednesday before the week in which they are to be discussed in section and/or to be relevant to homework assignments (see below).

Text:

No textbook, *per se*, is available for this course. However, Irwin has completed a draft of a book specifically for this course; the relevant chapter(s) will be posted on the course website at the end of the week of class meetings to which each is germane.

Homework:

Homework assignments will involve qualitative and quantitative parts, with the mixture varying, and will be based upon both class meetings and reading assignments. Homework will be distributed via the class website, most often on Monday evenings, and will be due the following Monday at the beginning of class. **Collaboration among students in solving homework problems is allowed, but each student must separately and individually write her or his own solutions for submission.** Homework assignments will taper off towards the end of the term to allow more time for students to work on their term projects (see below). Homework submitted late will have 10% of its total score deducted for each day's lateness; penalty avoidance will be possible if advance permission for the lateness is obtained from your TF or if official and cogent documentation of the reason for lateness is provided. However, in no case can homework be handed in more than two days late as solutions will usually be posted by Wednesday evenings and discussed as needed in the section meetings (see below) that directly follow.

Term Project:

The term project provides an opportunity to explore a topic that is directly related to this course, is clearly a direct extension of material from this course, or is on a topic of current societal concern. The project may be an individual project or a group project, with no more than three members in any one group. The project may, for example, involve data gathering and hypothesis testing, be wholly descriptive, or be a multimedia presentation, such as a 10-12 minute video explaining a course-related topic to high school students, in **all** cases using an evidence-based approach. Within these guidelines, we encourage creativity. For those who wish more guidance on a choice of topic, we will be happy to provide it. **Each project must be approved by the relevant TF**. A 1-page written project proposal should be submitted to her or him in lecture on **Monday, 11 March**. We will give feedback on each proposed project in section or via email no later than the week after spring break **(**begins **Monday, 25 March)**. A group project may be carried out with the group members being, collectively, in more than one section, but each member must have the project approved by her or his own TF (and, in such cases, the term project will be graded jointly by the TFs of all students involved). Written term projects will be due on **Wednesday, 1 May; the length of each should be about 10 – 15 pages (standard size paper and font, double spaced) for individual projects and longer for group projects, but not necessarily nearly so much as proportionately.** Projects requiring presentations will be scheduled for **Monday, 6 May**; any required A/V equipment is to be requested via the relevant TF on or before **Monday**, **29 April**.

Exams:

The in-class midterm will be **Wednesday, 27 March,** to avoid interference with due dates for senior theses. It will be about one-third short answer, one-third problems (needed formulas and values of constants will be provided, along with "distractors"), and one-third essay questions. We will distribute a study guide in a timely fashion and hold review session(s) as exam time nears.

The final will be the standard three-hour exam; its structure will follow the pattern of the midterm exam, with a study guide distributed and review session(s) scheduled as exam time nears. The final exam will cover the course such that, together with the midterm, all three parts of the course will receive about the same amount of the total exam time. The exam will take place on **a date and time as yet unknown.**

Both exams will be closed book and calculators will neither be needed nor allowed.

Regrading:

A student who believes that there have been one or more errors made in grading either her/his homework and/or midterm, may present the reasoning first to the TF and, as a final resort, to Irwin. Such presentations should be made within 10 days of the return of the graded work.

Grades:

Grades for this course will be determined by five components:

Lecture (1/3) and Section (2/3), Attendance and Participation:	20%
Homework:	20%
Midterm:	15%
Term Project:	15%
Final Exam:	30%

with final grades, if efforts were made, being determined on a curve, consistent with general practice for SPU and SLS courses.

Class Meetings and Sections:

Class meetings are on every **Monday and Wednesday from 12:00pm – 1:15pm, in the Science Center, during the Spring term, in Lecture Hall A**. In addition, there is a required weekly **one-hour section** on **either Thursday or Friday**, with times chosen based on student schedules. Section times and locations will be available as soon as feasible after enrollment is set. Sections will be devoted mostly to reviewing material discussed in class meetings, to solving practice problems, and to exploring particularly fascinating concepts for which there was insufficient time to delve deeply enough in class meetings. In addition, there will be three sections devoted to labs. One, an astronomy lab, will be held on the 8^{th} floor of the Science Center, where the Observatory is located, to enable students to gain experience making observations and analyzing the results, via determining a fundamental characteristic of the sun. (To allow for inclement weather, alternate dates will be planned.) The second will involve a trip to the Harvard Museum of Comparative Zoology to examine fossils, and/or to the museum of the Department of Earth and Planetary Sciences to observe meteorites as well as earth and lunar rocks. The third will be a lab relevant to molecular genetics.

Those unable to attend section for a given week due to a conflict, should attend another section. Email both the section leader and the leader of the make-up section (all email addresses will be available on the website, once known) to confirm attendance. Please consult with your TF if you would like further guidance.

Students with Special Needs:

Any student needing academic adjustments or accommodations is requested to present her/his letter from the Accessible Education Office (AEO) to, and speak with, Irwin by the end of the second week of the term. Failure to do so may result in his inability to respond in a timely manner. All discussions will remain confidential with the TFs and Irwin, although AEO may be consulted to discuss appropriate implementation.

Professor and TF Contact Information:

Irwin Shapiro - Professor

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Tarraneh Eftekhari - Head TF (astronomy)

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Daniel Buonaiuto – TF (biology)

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Video and Slide Access From Class Meetings:

This course is videotaped and each video will be posted on the course website between about 24 and 72 hours after the class meeting. Slides shown at each class meeting will also be posted on the website, either the evening following the class meeting or, at the latest, by the end of the week the class meeting was held.

Class Meetings Outline:

This course is divided into three main sections, as noted above:

1. Unveiling the Universe ("looking up")
2. The Earth and its Fossils ("looking down")
3. The Story of Life ("looking in")

Each section extends over about a month and is divided into subsections, some of which will spread over more than one class meeting and some over less.

Introduction

We first stress the "philosophy" underlying the course: What are the basic ingredients of science and what do we mean by the Unity of Science? Why is it a useful concept and how is it to be applied? How do we approach the treatment of the various topics? And, how do we provide the background science needed for understanding them?

Part 1: Unveiling the Universe

We describe the mostly amazing processes by which humans have been able to learn so much in such a relatively short time about the nature of the universe and yet, in a seeming contradiction, be confronted by ever deeper puzzles.

1.1 Pattern Recognition

From our vantage point of knowledge, it is hard to identify with ancient peoples who did not have any heritage of scientific investigation of their world. Nonetheless, we try. What did they think moved in the sky, what did not? How did they decide? What patterns did they notice? What periodicities? How did they interpret these patterns and periodicities to form a model of the universe? How did these interpretations affect their daily lives, if at all?

1.2 Measurements and Models

How did observations and measurements of the positions of sky objects of ever-increasing accuracy help lead us to more sophisticated models, indeed to dramatic changes in our world view? We trace this road through the practical and conceptual advances made principally by eight key participants: Ptolemy, Copernicus, Brahe, Kepler, Galileo, Roemer, Newton, and Einstein. For example, we discuss Einstein's theories of special and general relativity, their motivations, and some of their tests.

1.3 Dilemmas of Distance

How did astronomers determine the almost unimaginably vast distances between objects in space? We discuss the progress made through direct measurements, through measurements of parallax, and through powerful proxies that eventually extended our reach to nearly the most distant part of the universe.

1.4 Structure of the Universe

An early 20^{th} century debate concerned the structure of the universe, typified by the issue: One galaxy or many? In the direct aftermath of the resolution, Hubble obtained evidence that the universe is expanding. We describe how this result was obtained and its implications.

The consequent prediction of the Big Bang, and the later discovery of strong evidence for it, were dominant events in modern cosmology. We trace these events and their implications for our modern model of the structure of the universe.

1.5 Composition of the Universe

Determining the composition of the universe has been actively pursued over more than a century, punctuated by several major surprises from observations, the last barely 21 years ago – before many current Harvard College students were born. We now think that what we know and love as ordinary matter constitutes a rather small fraction of the total mass-energy in the universe. The rest consists of so-called *dark matter* (we cannot see it and have no idea of its makeup) and *dark energy* (a sort of antigravity, at present also totally mysterious). This situation implies that a dramatic change in our model of the universe might well be needed and, indeed, in some of our fundamental "laws" of physics. We discuss these discoveries as well as their implications for the ultimate fate of the universe.

Part 2: The Earth and Its Fossils

We turn from the heavens and gaze at the ground (and below), to investigate our strange and wonderful home planet, its physical characteristics, and especially the revolution that culminated in the fact-supported theory of plate tectonics. We also discuss fossils and their contribution to our knowledge of the earth's history, including the age of dinosaurs and reasons for its sudden end.

2.1 Shape and Size of the Earth

For millennia human populations were confined to relatively local regions on the earth's surface, and seemed to not show much concern about either the size or the shape of their planet. Gradually, inquisitive individuals devised increasingly clever ways to take the measure of the whole planet. We investigate some of their approaches and results, from ancient to modern.

2.2 Mass of the Earth

How can we determine the mass of the earth? There are earth-bound and astronomical ways, which we shall contrast, including the, perhaps apocryphal, effect their original disagreement had on Newton's publication of his universal "law" of gravitation.

2.3 Structure of the Earth

How can we find out what's inside the earth? We can't just dig to the center and see what we pass on the way. But we can and do listen to the noises it makes and via clever inference determine properties of its interior – a vast subject (seismology), which we explore in outline and expose some key results.

2.4 Age of the Earth

How old is the earth? This question captivated many through the ages, progressing from the realm of religion to a very important subject of science by the mid 19th century. We describe the main controversy, the battle about the age between geologists and physicists, primarily Lord Kelvin, with the time that might be needed for Darwinian evolution being part of the high-stakes background.

Final resolution of the controversy was not achieved until early in the 20th century and was based then on discovery of properties of matter unknown to the mid 19th century scientists waging the battles.

2.5 The Wegener Hypothesis: Drifting Closer to the Truth

In the first part of the 20th century, a German meteorologist, Alfred Wegener, made a sweeping and shocking hypothesis – that the continents are not fixed on the earth's surface, but rather are (slowly) moving with respect to each other. These heretical views were attacked strongly by contemporary geophysicists, and his proposal – commonly referred to at that time as *'continental drift'* – was not generally accepted until decades after his death. We explore the puzzles that led Wegener to his bold conclusion and the main reason that it was opposed.

2.6 Plate Tectonics: The Shifting Surface of the Earth

Wegener's hypothesis of continental drift did not explain how the seemingly solid earth's crust could be composed of large pieces that were in relative motion (what was the "motor" driving the motion?). The later uncovering of *plate tectonics,* a concept broader in scope than continental drift, and the mechanisms behind it, constitute one of the 20th century's great detective stories, one that dramatically changed our view of the earth. We recount the evidence, primarily magnetic, that supports this concept, and also describe how we are now able to measure the relative motion of plates with nearly unbelievable accuracy: over distances of thousands of kilometers, errors under a millimeter per year from less than a year of measurements.

2.7 Fossils: Window On the Past

Also dependent for interpretation on the age issue and on plate tectonics are fossils. Although they had been uncovered and examined by curious individuals over millennia, only in the 18^{th} and early 19^{th} centuries did systematic efforts start to unearth and understand fossils as the remains of prehistoric creatures. (One notable exception was the prescient work of Leonardo da Vinci over a hundred years earlier.) We discuss how fossils are formed; the history of fossil discovery; how fossils were interpreted (and reinterpreted) through time; and the profound role that they continue to play in aiding our understanding of life's past, a subject to which we return in Part 3 of the course.

2.8 The Mysterious Disappearing Dinosaurs

Ever since the discovery of a nearly complete dinosaur fossil in the mid-19^{th} century, these creatures have fascinated humans of all ages. We examine in detail the evolution and characteristics of one type, Sauropods, the largest land animal ever to roam the earth.

All dinosaurs disappeared from the scene rather abruptly, about 66 million years ago. Why? This question puzzled and intrigued scientists for decades. We mention some of the different explanations that have been given for dinosaur extinction, and concentrate on the evidence that led a scientist-detective team to a remarkable conclusion, yielding after about 30 years of wrangling a nearly total consensus among scientists on this issue: an asteroid (or comet) did it. We end with a discussion of other findings that led some scientists to break with this consensus and conclude: volcanism did it (probably with critical help from the asteroid or comet).

Part 3: The Story of Life

We treat our increasing, but still woefully incomplete, understanding of the origin of life and its evolution. Darwin's and Wallace's independent, nearly identical ideas on evolution gave this story order and direction, but left open the critical question of how biological traits are passed from generation to generation. After discussing Mendel's introduction of careful, quantitative experiment to biology, we trace the inheritance story from Miescher, the discoverer of DNA, through Watson and Crick to the modern day, describe applications to other sciences, and finish with our attempts to seek evidence of life beyond the earth.

3.1 Life on Earth

Earth is teeming with life, especially the microscopic variety. Why so pervasive? Why so diverse? How did it all start? How do we make sense of life? Is ours the only kind? These questions are daunting. First steps towards addressing them, taken largely in the 18^{th} and first part of the 19^{th} centuries, involved primarily classifications, which do not answer fundamental questions but form a useful base of organized data. Coupled now with a far deeper understanding of chemistry and physics, we are better able to address, but not yet resolve, the fundamental questions.

3.2 Darwin, Wallace, and the Theory of Natural Selection

All educated people, almost by definition, know about Darwin's theory of evolution and its basis, natural selection, whether or not they accept it. Alfred Russel Wallace, a contemporary of Darwin's, independently proposed a nearly identical theory. We recount evidence that led Darwin and Wallace to their theory, and describe the fiery reception it received in Victorian England and beyond. We dwell on some of the most valid of those critiques and their later resolution.

3.3 Origin of Experimental Biology

About the same time that Darwin and Wallace provided a rationale for the progression of traits and species, an obscure Austrian monk, Gregor Mendel, trained in physics, was quietly transforming biology from a descriptive into an experimental science with his careful studies on heredity in specially selected pea plants. We note how Mendel's work, apparently suppressed in his own time, was decades later rediscovered, providing "seeds" for our modern conception of genetics.

3.4 Why Do Elephants Never Give Birth to Mice (and Vice Versa)?

Neither natural selection nor Mendel's work on pea plants explained how heredity works on a molecular level. We discuss developments in physical science that enabled late 19th and early 20th century biologists to begin to probe life at the molecular level, which eventually pinned down the "motor" of heredity, explaining in the process why elephants never beget mice.

3.5 DNA as the Hereditary Material

We now think we know that of the enormous number of molecules present in the cell, DNA stands alone as the carrier of the main genetic material, the blueprint that specifies the traits of an organism. We trace the development of molecular biology from Friedrich Miescher's discovery in the late 1860s of DNA as a component of the nucleus of a cell to the critical experiments of the early-to-mid 20th century that seemed to cement DNA's place as the 'molecule of life,' and set the stage for uncovering its structure.

3.6 Double Helix

Research in molecular biology started to explode soon after 25 April 1953, the date of publication of James Watson and Francis Crick's famous proposal of a double helix structure for DNA. We describe the detective story leading to this discovery, with its intrigues and false starts.

3.7 Decoding DNA

The double helix brought a new clarity to molecular biology, enabling scientists to begin to systematically uncover the mechanisms by which instructions contained in a DNA blueprint are converted into a living organism. We describe some of the key experiments that contributed to our understanding of this process, and point out some of the huge holes remaining in our knowledge.

3.8 The Tree of Life

Our attempts to understand the origin and evolution of life are still very primitive and grossly incomplete in many respects. We discuss efforts to understand the origin of life and some of the reasons why it is such a difficult problem. Nonetheless, the progression of life - after the formation of the cell - can be usefully described in rough analogy with a tree. Roots represent the earliest forms of life, and leaves the latest. Construction of the tree can follow either of two paths: use of the fossil record, or detailed comparisons of DNA molecules across all living entities, or a combination of these two. Each path has its own strengths and weaknesses. How consistent are the resultant trees and how can each be used to improve the other, yielding a more robust single product? We explore the history and present status of this research, including an example of the primary use of each path, fossils for the origin of whales, and DNA for the origin of polar bears. We also discuss exceedingly unusual creatures, such as tardigrades, and how they might fit into a tree of life. We end with a description of a novel type of laboratory experiment that explores evolution in a controlled setting and that has already yielded unexpected results.

3.9 Applications to Human Lives

We describe the latest technique - CRISPR Cas 9 – used to modify DNA in a precise manner. And we discuss the use of our knowledge of DNA in helping to understand human history, such as our spread around the world, our inheritance from Neanderthals and other early hominids, and the variations of pathogens and their effects, for the main example, on the bubonic plague. Finally, we also describe the invention and use of a fruitful application to forensics - DNA fingerprinting.

3.10 Life Beyond Earth?

Is there life on other planets or satellites? Will such life resemble life here? In what ways? What are the necessary ingredients for life? Humans have posed these general questions and argued about possible answers for well over a century. Only over the past few decades have we learned enough about planets in and beyond our solar system to fruitfully seek evidence of life elsewhere in the universe. Using tools described in part in the first part of the course (and hence completing the 'cycle'), we describe how new planets have been discovered, and the surprises that were thus disclosed. We also discuss other tools and methods at our disposal that might one day allow us to reliably identify the presence of life on other planets or their satellites. Finally, we consider the search for extraterrestrial intelligence and the problems associated with communications with any such beings.

We hope that you enjoy this class and we encourage constructive feedback. The course will be somewhat different in content and organization from last year reflecting lessons learned from everyone involved. We expect the course to continue to evolve. So please share your thoughts and concerns with us at any time, anonymously or not – your choice!