

# Michigan Math and Science Scholars Courses for 2009

## **ASTRONOMY**

### **Climbing the Distance Ladder: How Astronomers Survey the Universe (Session 1)**

Instructor: Philip Hughes

The furthest objects that astronomers can observe (the nuclei of active galaxies) are so distant that their light set out when the Universe was only 800 million years old, and has been traveling to us for about 13 billion years -- most of the age of the Universe. Even the Sun's neighborhood -- the local part of our Galaxy, where astronomers have successfully searched for planets around other stars -- extends to hundreds of light years. How do we measure the distance to such remote objects?

Certainly not in a single step! Astronomers construct the so-called "Distance Ladder", finding the distance to nearby objects, thus enabling those bodies to be understood and used as probes of yet more distant regions. The first step on this ladder is to measure the distance to the planet Venus, by timing the round-trip for radar waves bounced from its surface. Knowing the laws of planetary motion, we can use information to get the distance to the Sun. Knowing the distance to the Sun, we can use the tiny shift in the apparent position of nearby stars as the Earth orbits during a year, to "triangulate" the distance to those stars. And so on out: through the Galaxy, the local group of galaxies, the local supercluster, to the furthest reaches of what is observable.

This class will explore the steps in this ladder, using lectures, discussions, demonstrations, and computer laboratory exercises. We will make frequent digressions to explore the discoveries made possible by knowing the distance to objects (such as gamma-ray bursters and the acceleration of the Universe's expansion), and get hands-on experience of using distance as an exploratory tool, by using a small radio telescope to map the spiral arm pattern of our own galaxy, the Milky Way.

## **APPLIED PHYSICS**

### **Introduction to Laboratory Research Methods (Session 2)**

Instructor: Louise Hecker

This course will introduce students to some of the basic concepts of laboratory research. Students will learn hands-on laboratory techniques such as tissue isolation, cell culture, and histology. Lectures will introduce topics such as the scientific method, experimental research design, and the history and science behind the techniques they will be learning in the lab. Students will set up, execute, analyze, and present their own research experiment.

## **CHEMISTRY**

### **Surface Chemistry (Session 2)**

Instructor: Zhan Chen

This course will be divided into three units: applications, properties, and techniques. The first unit will introduce students to surface science that exists within the human body, surfaces in modern science and technology, and surfaces found in everyday life. Our bodies contain many different surfaces that are vital to our well-being. Surface reactions are responsible for protein interaction with cell surfaces, hormone-receptor interactions, and lung function. Modern science has explored and designed surfaces for many applications: anti-biofouling surfaces are being

## Michigan Math and Science Scholars Courses for 2009

researched for marine vessels; high temperature resistant surfaces are important for space shuttles; and heterogeneous catalysis, studied by surface reactions, is important in industry and environmental preservation. The usefulness of many common items is determined by surface properties: contact lenses must remain wetted; while raincoats are designed to be non-wetting; and coatings are applied to cookware for easy clean-up.

The second unit will examine the basic properties of surfaces. Lectures will focus on the concepts of hydrophobicity, friction, lubrication, adhesion, wearability, and biocompatibility. The instrumental methods used to study surfaces will be covered in the last unit. Traditional methods, such as contact angle measurements will be covered first. Then vacuum techniques will be examined. Finally, molecular level *in situ* techniques such as AFM and SFG will be covered, and I will arrange for students to observe these techniques in our lab.

Multimedia powerpoint presentations will be used for all lectures. By doing this, I hope to promote high school students' interest in surface science, chemistry and science in general. A website introducing modern analytical chemistry in surface and interfacial sciences will be created.

### ECOLOGY AND EVOLUTIONARY BIOLOGY

#### **Dissecting Life: Human Anatomy and Physiology (Offered Session 1 and Session 2)**

Instructor: Glenn Fox

This course will be offered Session 1 *and* Session 2. This is the same course, offered in both sessions due to its popularity! Do not sign up for it twice.

Dissecting Life will lead students through the complexities and wonder of the human body. Lecture sessions will cover human anatomy and physiology in detail. Students will gain an understanding of biology, biochemistry, histology, and use these as a foundation to study human form and function.

Laboratory sessions will consist of first-hand dissections of a variety of exemplar organisms: lamprey, sharks, cats, etc. Students may also tour the University of Michigan Medical School's Plastination Laboratory where they can observe human dissections.

#### **Explorations of a Field Biologist**

Instructor: Sheila K. Schueller

There are so many different kinds of living organisms in this world, and every organism interacts with its physical environment and with other organisms. Understanding this mass of interactions and how humans are affecting them is a mind-boggling endeavor! We cannot do this unless we at times set aside our computers and beakers, and, instead, get out of the lab and classroom and into the field - which is what we will do in this course. Through our explorations of grasslands, forests, and wetlands of southeastern Michigan you will learn many natural history facts (from identifying a turkey vulture to learning how mushrooms relate to tree health). You will also become adept at practicing all the steps of doing science in the field, including making careful observations, testing a hypothesis, sampling and measuring, and analyzing and presenting results. We will address questions such as: How do field mice decide where to eat? Are aquatic insects affected by water chemistry? Does flower shape matter to bees? How do lakes turn into forests? Learning how to observe nature with patience and an inquisitive mind, and then test your ideas about what you observe will allow you, long after this class, to discover many more things about the natural world, even your own back yard. Most days will be all-day field trips, including

# Michigan Math and Science Scholars Courses for 2009

hands-on experience in restoration ecology. Toward the end of the course you will design, carry out, and present your own research project. Note: This class is not for students who prefer to be indoors!

## MATHEMATICS

### Combinatorial Combat (Session 1)

Instructor: Mort Brown

We will play and analyze a variety of two person competitive strategic games. All of these games will have simple rules, perfect information (i.e., you know everything that has happened at each point in the game, no luck involved), win lose or draw, and be interesting and challenging. We will study such notions as "formal strategy", "game tree" and "natural outcome" and investigate methods of solving some of the games. We'll study Hex and a related game Y and an unrelated game "Poison Cookie" and examine John Nash's (he of the Beautiful Mind) proof that the first player has a winning strategy in each of these games even though nobody knows what the winning strategy actually is! Games such as Nim and Fibonacci Nim will allow us to see how some good math can be used to solve many games. Other games such as "Dwarfs and Giants", "Fox and Geese", and Dodgem will be analyzed without any mathematics but good logical skills. We'll also come across many games that are "isomorphic" (i.e., the same) even though they do not seem to be at first. If you ever played games such as Tic Tac Toe, Connect Four, Othello, Gomoku (Pente), Chess and Checkers; this course is right for you. However, no previous knowledge of any specific game is required.

### Congruent Numbers: When can a Number be a Triangle? (Session 2)

Instructor: Bryden Cais

When can a whole number be the area of a square whose side length is a rational number? The answer is easy: exactly those whole numbers that are squares: 1,4,9,16,...

It is natural to ask the same question for other simple geometric figures, like right triangles. A positive whole number is called congruent (and not "a triangle" as it maybe should be) if it is the area of a right triangle whose side lengths are rational numbers. For example, 6 is congruent because it is the area of the right triangle with side lengths 3,4,5. Likewise, the triangle with side lengths  $3/2$ ,  $20/3$ , and  $41/6$  is a right triangle with area 5, so 5 is a congruent number. The analogue of our easy question about squares is the "congruent number problem", first formulated by Arab mathematicians in 972 AD: which positive whole numbers are congruent?

This turns out to be a very difficult and deep problem, whose answer is still unknown today! For starters, as opposed to the situation with squares, it isn't obvious that there are even infinitely many congruent numbers since if two rational side lengths for a right triangle are selected at random, the third side generally will not be a rational number. Nonetheless, the ancient Greeks knew a method ("Pythagorean triples") of producing infinitely many examples of congruent numbers. However, it took nearly two-thousand years for mathematicians (specifically Fermat, in the year 1659) to prove that the number 1 is not a congruent number!

In the latter half of the twentieth century (specifically 1983), the mathematician Jerrold Tunnell exploited a deep connection between congruent numbers and the geometry of cubic curves to provide a complete (albeit conjectural) classification of all congruent numbers. This classification says, among many other things, that if a prime number is of the form  $p=8n+3$ , then  $p$  is not congruent but  $2p$  is. (As a side note, if you can prove that the conjectured classification of congruent numbers is correct, you could win a million dollars! Just google "BSD conjecture" and "Tunnell Theorem" for more information).

## Michigan Math and Science Scholars Courses for 2009

We will investigate the "congruent number problem" posed above and learn a lot of interesting number theory in the process. Our journey will begin with the ancient Greeks, and will take us through Fermat's method of infinite descent, elliptic curves, modular forms, Tunnell's theorem and the infamous BSD conjecture.

### **End of the World Mathematics (Session 2)**

Instructor: Alexei Kolesnikov

An old legend says that in the center of the world rests a brass plate with three vertical diamond needles. On one of these needles, at the beginning of time, God placed 64 disks of pure gold, the largest disk resting on the brass plate, and others getting smaller and smaller up to the top one. A group of priests works day and night to transfer the disks from one needle to another, moving only one disk at a time and never placing a larger disk onto a smaller. After the entire tower is moved, the plate, the needles, and the disks will crumble to dust, the priests will vanish, and the world would end. Will the priests be able to transfer the disks; and if yes, how long would it take to complete the task?

An eccentric math professor arranges his 31 students in a circle. He then goes around the circle giving every other student a really hard take-home problem. Upon receiving a problem, each student immediately leaves to work on it leaving fewer students in the circle. The professor goes around again and again giving out hard problems to every other remaining student until there is only one student left; that student gets an "A" without having to do any work. If you are in that class, and would like to get a free "A", where should you stand in the circle?

Both questions can be easily answered with the help of recurrence relations, an important mathematical tool widely used in mathematics and computer science. Recurrence relations will be a central theme of our course. We will also have several opportunities to point out that mathematics is full of surprising connections. For example, we will see how the formula for solving quadratic equations can be used to get a formula for Fibonacci numbers (the numbers in the sequence 0, 1, 1, 2, 3, 5, 8, ..., where every number is the sum of two preceding numbers).

### **Fibonacci Numbers (Session 2)**

Instructor: Mel Hochster

The Fibonacci numbers are the elements of the sequence 0, 1, 1, 2, 3, 5, 8, 13, 21, 34, 55, ... , where every term is simply the sum of the two preceding terms. This sequence, which was originally proposed as describing the reproduction of rabbits, occurs in astonishingly many contexts in nature. It will be used as a starting point for the exploration of some very substantial mathematical ideas: recursive methods, modular arithmetic and other ideas from number theory, and even the notion of a limit: the ratios of successive terms (e.g.,  $13/8$ ,  $21/13$ ,  $55/34$ , ...) approach the golden mean, already considered by the ancient Greeks, which yields what may be the most aesthetically pleasing dimensions for a rectangle. As one by-product of our studies we will be able to explain how people test certain very special but immensely large numbers for being prime. We'll also consider several games and puzzles whose analysis leads to the same circle of ideas, developing them further and reinforcing the motivations for their study.

### **Images and Mathematics (Session 2)**

Instructor: Nkem Khumbah

Suppose you are given a picture (an image) that has been partially damaged –say your grandparent's picture or childhood video, or an image that is blurred, and you need to find (some) contents of the original image. Such problems are very common in much of the visual technology

## Michigan Math and Science Scholars Courses for 2009

that facilitates our lives. Astronomers study the universe by taking and analyzing pictures of the deep skies (how could they tell in that picture that there was a tiny star being formed?). Modern medicine continuously relies heavily on images of human anatomy to tell abnormalities in different parts of the body, or guide surgical interventions. Oil companies use seismic images to determine the presence of oil deposits under the earth surface. Aviation security would like to have technological tools that can recognize people automatically from their picture; to detect dangerous people and avoid some of the costly long lines at airports. Such technology could also find use as picture IDs at ATMs and other high security zones, in lieu of passwords.

The field of image analysis is one of the most active sources of inspiration for the uses of mathematics. This course will be about the mathematics that underlies the analysis of images and imaging technology. We will introduce our students to methods used to study different problems arising in image analysis, like image segmentation, inpainting and reconstruction; but primarily, we will start exploring the abstract mathematical topics involved, like modeling, inverse problems, harmonic analysis, data compression and information theory. All of these fields, with a far longer history than image analysis, continuously find practical and new uses in the development of many technologies. The course will have reading/research, classroom mathematics and computer lab components. In the labs, we will use MATLAB; a general-purpose mathematical package to put our mathematics into practice. For fun, students are encouraged to bring along their own pictures to test the mathematics they will learn.

### **Mathematical Modeling in Biology (Session 1)**

Instructor: Trachette Jackson and Patrick Nelson

Mathematical biology is a relatively new area of applied mathematics and is growing with phenomenal speed. For the mathematician, biology opens up new and exciting areas of study while for the biologist, mathematical modeling offers another powerful research tool commensurate with a new instrumental laboratory technique. Mathematical biologists typically investigate problems in diverse and exciting areas such as the topology of DNA, cell physiology, the study of infectious diseases such as AIDS, the biology of populations, neuroscience and the study of the brain, tumor growth and treatment strategies, and organ development and embryology.

This course will be a venture into the field of mathematical modeling in the biomedical sciences. Interactive lectures, group projects, computer demonstrations, and laboratory visits will help introduce some of the fundamentals of mathematical modeling and its usefulness in biology, physiology and medicine.

For example, the cell division cycle is a sequence of regulated events which describes the passage of a single cell from birth to division. There is an elaborate cascade of molecular interactions that function as the mitotic clock and ensure that the sequential changes that take place in a dividing cell take place on schedule. What happens when the mitotic clock speeds up or simply stops ticking? These kinds of malfunctions can lead to cancer and mathematical modeling can help predict under what conditions a small population of cells with a compromised mitotic clock can result in a fully developed tumor. This course will study many interesting problems in cell biology, physiology and immunology.

### **Mathematics of Decisions, Elections, and Games (Session 2)**

Instructor: Michael A. Jones

You make decisions every day, including whether or not to sign up for this course. The decisions you make under uncertainty says a lot about who you are and how you value risk. To analyze such decisions and provide a mathematical framework, utility theory will be introduced and

## Michigan Math and Science Scholars Courses for 2009

applied to determine, among other things, the monetary offer the banker makes to contestants in the television show *Deal or No Deal*.

Elections are instances in which more than one person's decision is combined to arrive at a collective choice. But, how are votes tallied? Naturally, the best election procedure should be used. But, Kenneth Arrow was awarded the Nobel Prize in Economics in 1972, in part, because he proved that there is no "best" election procedure. Because there is no one best election procedure, once the electorate casts its ballots, it is useful to know what election outcomes are possible under different election procedures – and this suggests mathematical and geometric treatments to be taught in the course. Oddly, the outcome of an election often says more about which election procedure was used, rather than the preferences of the voters! Besides politics, this phenomenon is present in other settings that we'll consider, which include the Professional Golfers' Association tour which determines the winner of tournaments under different scoring rules (e.g., stroke play and the modified Stableford system), the method used to determine rankings of teams in the NCAA College Football Coaches poll, and Major League Baseball MVP balloting.

Anytime one person's decision can affect another person, that situation can be modeled by game theory. That there is still a best decision to make that takes into account that others are trying to make their best decisions is, in part, why John F. Nash was awarded the Nobel Prize in Economics in 1994 – which inspired the movie *A Beautiful Mind* about Nash, which won the Academy Award for Best Picture in 2002. Besides understanding and applying Nash's result in settings as diverse as the baseball mind games between a pitcher and batter and bidding in auctions, we'll examine how optimal play in a particular game is related to a proof that there are the same number of counting numbers  $\{1, 2, 3, \dots\}$  as there are positive fractions.

### **Mathematics and the Internet (Session 1)**

Instructor: Mark Conger

How do online computers find each other? How does email data travel over cables designed for television signals? How can gigabytes of information move over unreliable airwaves using unreliable signaling, and arrive perfectly intact? How can I have secure communication with a website run by a person I've never met? In Mathematics and the Internet, we'll answer these questions. We'll also learn to use abstract mathematical tools for studying such systems, including graph theory, probability, logic theory, and coding theory. All of these fields, heavily studied before the internet, find new practical uses every day. For fun, we will find out how to write computer code to automatically interact with and analyze the larger internet. We also try to build a calculator and a primitive cryptographic computer out of transistors and a few other parts lying around in Mark's garage.

### **MOLECULAR, CELLULAR AND DEVELOPMENT BIOLOGY**

#### **Genes to Genomics (Session 1 OR Session 2)**

Instructor: Santhadevi Jeyabalan

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# Michigan Math and Science Scholars Courses for 2009

This course will cover basic aspects of Mendelian and molecular genetics, and then focus on a few human disorders in detail. We will introduce human genome sequence as an aid to cloning the genes responsible for these disorders, and will demonstrate how comparative genomics allows genetic diseases to be studied using model organisms like yeast, *Drosophila*, nematodes and mice.

In addition to lectures, we will work with fruit flies, yeast and will do human DNA fingerprinting in a genetics laboratory. We will use computers to carry out molecular and phylogenetic analysis of DNA sequences. This class should provide an understanding of Human Genome Projects and recent advances in medicine.

## PHYSICS

### **The Physics of Magic and the Magic of Physics (Session 2)**

Instructors: Frederick Becchetti and Georg Raithel

Rabbits that vanish; objects that float in air defying gravity; a tiger that disappears and then reappears elsewhere; mind reading, telepathy and x-ray vision; objects that penetrate solid glass; steel rings that pass through each other: these are some of the amazing tricks of magic and magicians. Yet even more amazing phenomena are found in Nature and the world of physics and physicists: matter that can vanish and reappear as energy and vice-versa; subatomic particles that can penetrate steel; realistic 3-D holographic illusions; objects that change their dimensions and clocks that speed up or slow down as they move (relativity); collapsed stars that trap their own light (black holes); x-rays and lasers; fluids that flow uphill (liquid helium); materials without electrical resistance (superconductors).

In this class students will first study the underlying physics of some classical magic tricks and learn to perform several of these (and create new ones). The "magic" of corresponding (and real) physical phenomena will then be introduced and studied with hands-on, minds-on experiments. Finally, we will visit a number of research laboratories where students can meet some of the "magicians" of physics --- physics students and faculty --- and observe experiments at the forefront of physics research.

### **Roller Coaster Physics (Session 1)**

Instructor: [David Winn](#)

What are the underlying principles that make roller coasters run? By studying the dynamics of roller coasters and other amusement park rides in the context of Newtonian physics and human physiology, we will begin to understand these complex structures. Students first review Newtonian mechanics,  $a=F/m$  in particular, with some hands-on experiments using air-tables. This will then be followed by digital-video analysis of motion of some real-life objects (humans, cars and toy rockets) and student-devised roller coaster models. Then, a field trip to Cedar Point Amusement Park where students, riding roller coasters and other rides, will provide real data for analysis back at UM. Students will carry portable data loggers and 3-axis accelerometers to provide on-site, and later off-site, analysis of the motion and especially, the "g-forces" experienced. The information collected will then be analyzed in terms of human evolution and physiology; we shall see why these limit the designs of rides.

In addition to exploring the physics of roller coasters, cutting-edge topics in physics will be introduced: high energy physics, nuclear astrophysics, condensed-matter theory, biophysics and medical physics. Students will then have a chance to see the physics in action by touring some of

# Michigan Math and Science Scholars Courses for 2009

UM's research facilities. Students will have the opportunity to see scientists doing research at the Solid State Electronics Laboratory, the Michigan Ion Beam Laboratory and the Center for Ultrafast Optical Science.

By the end of the two-week session, students will gain insight and understanding in physics and take home the knowledge that physics is an exciting, real-life science that involves the objects and motions surrounding us on a daily basis.

## PROGRAM IN THE ENVIRONMENT

### **Crisis, Collapse, Resilience and Renewal (New Course!) (Session 1)**

Instructor: William Currie

In this course, students will construct and explore computer models of the environment as a dynamic system. The study of the environment involves learning across scientific disciplines as diverse as physics, biology, and anthropology. It involves efforts to understand complex interactions that make the unpredictable seem understandable, or the chaotic seem predictable, using tools and concepts from the study of dynamic systems. We will construct computer models to explore instabilities and tipping points in three types of environmental systems: Resource use and human population collapse on Easter Island, the effects of habitat loss and restoration on predator-prey dynamics in wildlife populations, and the interaction of sunlight, temperature, and plant ecology in regulating the stability of climate on a hypothetical planet called Daisyworld.

Mornings will be spent in an interactive lecture and discussion setting, while each afternoon will be spent in a state-of-the-art computer instructional laboratory where each student will work on his or her own computer. Through interactive exercises and hands-on learning, students will build models using Stella, a modeling software that uses visual, intuitive graphical model maps and that is designed to teach the principles of systems thinking and systems modeling. This is the same software used to teach modeling principles to undergraduate and graduate students studying the environment. Students will use this intuitive software to explore how the interconnections among parts of environmental systems interact to create stabilities, instabilities, dynamics and surprise. As a final project, students will work in groups to compete in a class contest to see which team can best manage the planetary climate using a Stella model.

This course will be taught in the Dana building on the UM central campus, home of the School of Natural Resources & Environment. The 100-year old Dana building was recently renovated as a "green" building using recycled materials and renewable energy. The building was awarded a Gold rating from the US Green Building Council through their LEEDS program (Leadership in Energy and Environmental Design), making it now the greenest academic building in Michigan.

### **"Why Here?" - Reading Diverse Landscapes (Session 2)**

Instructor: David C. Michener

You'll never look out the window the same way after this course! Landscapes can be 'read' for a great deal of information not evident to the untrained observer. We'll be conducting class outdoors and compare different but nearby landscapes to generate compelling questions that require field observations of various types to understand and resolve. In this field-intensive class we'll explore several University-managed natural and research areas in the Ann Arbor area to learn how to orient oneself to a landscape and begin to analyze important components. From our

# Michigan Math and Science Scholars Courses for 2009

field work, we'll address questions about the current vegetation and its stability in time; its past site history (post-settlement, pre-settlement) and future prospects. Current issues in biological conservation will raise themselves since some of the sites have native stands of rare plant species which we'll see and try to understand "why here?" We'll work with plant identification and survey skills on-site, as well as comparing photographic documentation and then better understand the limitations of our 'gut level' reading of the sites. We'll also examine areas commonly understood as "natural" that on inspection turn out to be designed and modified by humans. This may be a springboard into your future research interests here at UM!

No prior field-work or knowledge of the local climate, flora, fauna, geology, or history is expected.

## STATISTICS

### Sampling, Surveys, Monte Carlo and Inference (Session 1)

Instructor: Edward Rothman

Political candidates drop out of elections for the U.S. Senate and New York Governorship because their poll numbers are low, while Congress fights over whether and how much statistics can be used to establish the meaning of the U.S. Census for a host of apportionment purposes influencing all our lives.

Suppose we need to learn reliably how many people have a certain disease? How safe is a new drug? How much air pollution is given off by industry in a certain area? Or even how many words someone knows?

For any of these problems we need to develop ways of figuring out how many or how much of something will be found without actually tallying results for a large portion of the population, which means we have to understand how to count this by sampling.

And Monte Carlo? Sorry, no field trips to the famous casino! But Monte Carlo refers to a way of setting up random experiments to which one can compare real data: does the data tell us anything significant, or is it just random noise? Did you know you can even calculate the number  $\pi$  this way?!

The survey and sampling techniques that allow us to draw meaningful conclusions about the whole based on the analysis of a small part will be the main subject of this course.