Making Analogies: The Power and Limitations of Models when Exploring Advanced Physics Topics

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Overview:

Scientists use conceptual and mathematical models to make sense of or predict the behavior of the natural world. These models can take the form of images that portray the interactions between objects or systems (as when atoms are imagined to be small, moving balls), or the symbolic representations of certain quantities expressed as mathematical relationships (as when a formula is written for the energy of a system). In order to be successful citizens or scientists, high school students should be able to interact with conceptual and mathematical models in a number of ways. Students should be able to:

1) use models to make predictions about the natural world
2) recognize the inherent limitations of any model.
3) generate models, based on given data or relationships.
4) modify models to accommodate new data.
5) use conceptual models to work, at an intuitive level, with concepts or relationships that cannot otherwise be comprehended, save with mathematical models.

The majority of time in a physics class is devoted to the objective #1, with little time given to any of the other four. However, skills #2, #3 and #4 constitute much of the work of the scientist, as well as any reasonably introspective professional in any field. There has been much work in recent years to incorporate those skills into the science curriculum, encouraging students to look for and explain patterns in data, to explain their reasoning when performing calculations and to discuss multiple explanations for given phenomena. Skill #5 seems peculiar to the field of advanced physics, in that there are certain natural characteristics which can be modeled EXTREMELY accurately with mathematical tools, but absolutely defy modeling at a conceptual (and therefore intuitive) level. Over time, scientists have developed a compilation of conceptual models that, when applied appropriately and with the proper mental changes, re-forge the link between reality and human intuition. These conceptual models about mathematical models are sometimes called analogies. This unit attempts to show advanced high school physics students the utility in conceptual model generation (as it applies to physics topics, as well as other fields of study), familiarize them with some of the natural phenomena that require analogies to be understood at an intuitive level and to show them how to use the analogies to imagine things that cannot be imagined.

Rationale:

Science is the result of humans attempting to observe, organize and ultimately understand the natural world. In order to do so, natural phenomena must be filtered and re-processed, which supplants reality with a human representation of that reality. These representations may be numerical, verbal, pictorial or, in some cases, merely mental images or connections formed in the mind of the scientist. By creating an artificial reality and performing operations on their models, scientists are able to make predictions about the natural world or see connections between phenomena that would otherwise have remained hidden.

Most of science teaching at the high school level focuses on introducing students to the power of the scientific models that have been developed over the course of hundreds of years. These models have proven effective in that the predictions made correlate with the observations of the natural world - masses accelerate when forces are applied in a way described by Newton's model of the universe; gasses expand when heated according to the model proposed by Boyle, organisms resemble their parents according to the model suggested by Mendel. Obviously, modifications and elaborations of these models and myriad others have been developed in the years since their inception, but their importance is such that much of a high school science class is devoted to an exploration of these models, either by re-discovering them in lab, re-verifying their existence and accuracy, or re-telling the stories of that surround their discovery and evolution. Much research has been done on the best ways to deliver these models to the students, resulting in the development of inquiry based teaching, the emphasis on eminent scientist's biographical information and the exaltation of the "hands-on-activity."

In many cases, the models that are studied in high school biology, chemistry and physics are the tools for understanding visible, tangible phenomena and the models are comparatively easy to grasp. These conceptual models are almost like little movies that the students are asked to play in their heads, showing billiard balls colliding, strands of DNA coming apart and re-combining or blocks of wood sliding down ramps. These conceptual models can be used in conjunction with a "mathematical" model of the same situation; a model which is, again, a human's attempt to represent the natural phenomenon, but rendered in a away that can be manipulated and used to make predictions. The mathematical model relies on the translation of the natural phenomenon into symbols, which bear very little visual similarity to the objects or actions they represent. Students at the high school level often struggle with the translation between reality and the two types of models (conceptual and mathematical), sometimes making assertions about the natural world based on one model which do not correlate with their understanding of the other model. For example, students might calculate, using a mathematical model, that a thrown tennis ball has a velocity of 300 m/s, whereas they would never believe that as a natural phenomenon if they played that movie in their heads. Also, students might play the movie in their heads of a horizontally launched object striking the ground sooner than an object dropped from the same height, yet be able to manipulate the symbols correctly to show that time required to strike the ground is exactly the same. Depending on the student and his or her experiences, one type of model might be more consistently correct than the other, and one of the roles of the teacher is to make sure that both types of model, the conceptual and the math, are in accordance with the natural phenomenon represented.

There are a number of reasons that students might possess a deficient conceptual model, one that does not give an accurate description of reality. Some of the reasons are that humans have a limited capacity to imagine large numbers of objects, large numbers of interactions or long time-spans. Any student can imagine a box with a single marble rattling around inside of it, but their intuition is no longer able to make predictions about the situation if you populate the box with 6,000,000,000,000,000,000,000,000 tiny marbles all traveling at different speeds. Students can imagine a pendulum swinging back and forth, but may not be able to tell you where the pendulum bob will be if the metal pendulum is attached to a spring, mounted to the wheel of a rolling cart and subjected to a changing electric field. It is easy to imagine how a brown dog can give birth to white puppies, but it is much harder to imagine how a bacteria can be the ancient ancestor of an iguana.

There are a number of reasons why a student might possess a deficient mathematical model, one that does not give an accurate description of reality. If the student is not able to translate reality into symbols, then their mathematical model will be useless. At the basic level this means knowing that a house cat does not have a mass of 400 kg, and at the more advanced level it is manifest in an inability to write down an integral that can be used to calculate the rotational inertia of a solid disc (though they may be able to describe how they should "slice" the object and add up the pieces). If the students have not mastered the skills needed to manipulate the symbols correctly then, again, they will not have a useful model. This failure shows up when students cannot isolate a variable in an equation or take the derivative of a trig function.

Most of a high school physics class is devoted to strengthening the student's skills in using conceptual and math models. There are natural phenomena, however, that are best taught using a further level of abstraction, by creating a model of either the mathematical or conceptual model. These meta-models are often referred to as analogies, and are meant to allow the user to make predictions about models themselves. As an example, look at the way the energy of a system is calculated. The energy model of representing the world can be done with mathematical manipulations involving symbols like

$$47J \qquad\qquad \frac{1}{2}m\,v^{2} \qquad\qquad \int \vec{F}\bullet d\vec{r}$$

However, as a guide to understanding the symbolic manipulations, it is sometimes useful to think about energy as though it were pebbles in a series of cups. In the same way that different objects can have different amounts of energy, different cups can contain different numbers of pebbles. Different types of energy can be compared, in the same way that you could count how many pebbles are in the Kinetic Energy cup and compare it to the number of pebbles in the Gravitational Potential Energy cup. The amount of energy an object has does not spontaneously change, in the same way that pebbles do not magically appear, nor do they randomly disappear. Finally, if energy is transferred between one system and another the total amount of energy will be conserved, in the same way that if we move a handful of pebbles from one cup to another we have not made any pebbles, they have just changed location. This analogy allows an intuitive manipulation of the energy model, without any reference to the mathematics that provides a much more predictive model for the situation.

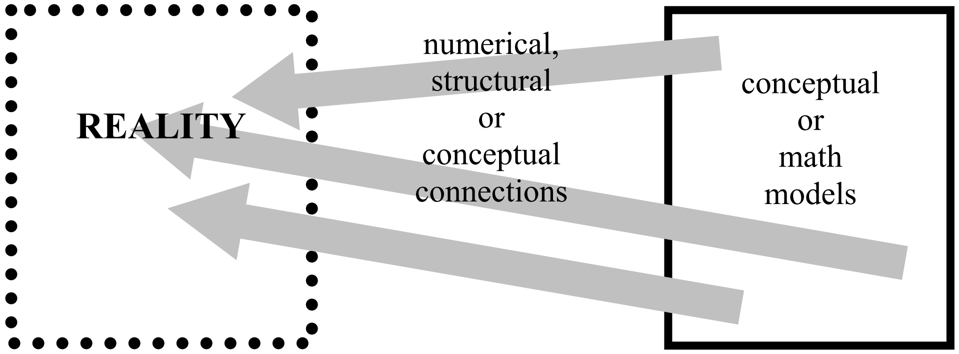
The use of analogies is extremely helpful in teaching many concepts, such as the water analogy when examining DC circuits, the water wave analogy when investigating sound, the city analogy when discussing the organelles in a cells or the penny flipping analogy when looking at radioactive decay. The benefits of introducing students to these concepts is that students are then able to use a conceptual model to gain some insight into a phenomenon which would otherwise require a math model to comprehend. It is often the case that a student only "gets" it when he or she has a functioning conceptual model of a situation, regardless of their ability to use a math model to analyze a situation.

Imagine the entire x-y plane.

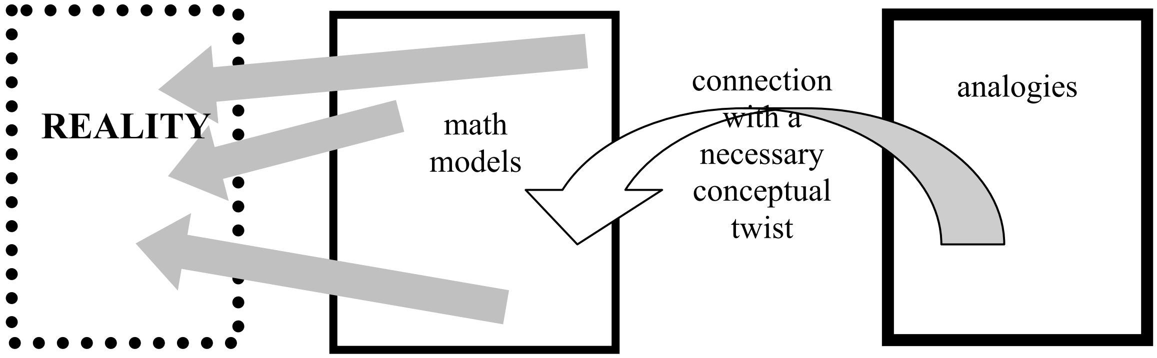
Of course, the mind balks at such a request. However, you can get some sense of this infinity by imagining walking along in a large, open field. Now imagine that the field doesn’t have an end to it - there is no row of trees surrounding it, there are no mountains in the distance, there is no line where the grass stops and water begins. The analogy (that the infinite x-y plane is like a big, boundless field) allows the user to bring to use his or her intuition when treating an otherwise incomprehensible concept. The fact that the analogy exploits a standard conceptual model ("like a big field") but adds a conceptual twist ("that has no edges") is what makes it useful for some advanced physics topics. Unimaginability is a characteristic of many natural phenomena described by quantum mechanics, general relativity and certain theories in high energy particle physics. The most accurate, predictive model humans have developed that describes the quantum mechanical behavior of a subatomic particle, (an electron, for example) is the mathematical model developed by Schrodinger. However, the average high school student would not be able to use Schodinger's wave equations to make sense of lab data or to make predictions about electron beam behavior because the mathematical techniques required to unpack the equations are well beyond any high school curriculum. Even if the student were able to perform the mathematical manipulations required to get an answer, the answer would not conform to any familiar experience and his or her “intuition” would be useless. Scientist's themselves, looking for ways to develop an intuition about quantum mechanics, have made the analogy that the electron sometimes behaves LIKE a wave - wave phenomena being a tangible and relatively easily understood natural occurrence. The wave picture of the electron is an analogy designed to make understandable, at the gut-level, an actual natural phenomenon which is directly unobservable and absolutely incomprehensible in its original state, but rendered, via mathematics, representable and predictive. With practice, high school students should be able to use the analogies that represent the mathematical models, even though they may be many years from being able to exploit the mathematical models needed to make testable predictions about reality.

The use of models and analogies and their relationship to reality is as follows:

The Standard Models:



Analogies:



In cognitive science literature, analogies have been defined as "a correspondence in some respects between concepts, principles or formulas otherwise dissimilar. More precisely, it is a mapping between similar features of these concepts, principles or formulas." [Glynn, et al. 1989]. (as quoted in Parida, B.K.) Although there is a lot of research about the ways in which analogies are formed, the types of analogies created and the context in which different analogies emerge, there is not a lot of data about the ultimate efficacy on student learning by use of analogy making in the classroom [Gabel and Sherwood 1980] (as quoted in Parida, B.K) However, the use of analogies by professional scientists and the correlation between analogical thinking and scientific productivity is well documented: "…[R]esearch on the use of analogy in science has shown that scientists frequently use analogy (Dunbar 1993; 1995; 1997b; 1997c) We found that scientists use anywhere from three to 15 analogies in a one hour laboratory meeting (see Dunbar, 1999a)." (Dunbar p.126) It appears that a facility with analogies is required of anyone who wishes to communicate with scientists or to be able to reason as a scientist: "frequent use of analogy was one of the chief predictors of research productivity" (Gentner p.106). It is important, then, that students are given analogy-making tools and shown how those tools can be employed effectively to strengthen existing content knowledge about a subject, improve recall about particular topics, speed acquisition of new ideas, and (for this unit) enable them to mentally grasp otherwise unimaginable ideas.

As a framework for structuring the instruction in this unit, I use Glynn's Teaching-With Analogies (TWA) model (Glynn, 1991), which distinguishes between 6 different parts of analogy teaching:

1. Introduce target (where "target" in this case refers to the new concept for the student)
2. Cue retrieval of analog (reminding the student of a familiar situation or idea)
3. Identify relevant features of target and analog (lay the groundwork for the connections by emphasizing certain aspects of both the target and the analog, without drawing connections between the two)
4. Map similarities (explicitly state how the specific features of the target are similar to the features of the analog)
5. Draw conclusions about target (show how the analogy provides insight about the target based on prior information contained in the analog)
6. Indicate where the analogy breaks down (a step that many researchers point to as valuable in preventing student misconceptions)

When teaching about certain topics in high-energy physics, I think that it is necessary to include a step in between steps 5 and 6. This step (step 5A), would be to clearly state the mental alteration that allows a more complete mapping of one concept onto another. This is different from a traditional step 6, because it does not invalidate the analogy in certain domains; it makes the connections between target and analog even stronger. As an example, when teaching about the multi-dimensional curvature of space, step 5A would be to state how a 4-D space appears to humans just as 3-D space appears to a 2-D creature. The analogy is mapping the analog (3-D space) onto the target (4-D space) by adding the mental step of momentarily pretending to be 2-D creatures. This trick for imagining 4-D space is not part of the analogy (hence not covered by step 2), it is not a limitation of the analogy (hence not covered by step 6) and it is not a feature that is common to the target and the analog (hence not covered by step 4). But students need this additional bit of information in order to make the analogy useful.

As an aid to understanding analogies presented in literature and textbooks, I will ask students to generate their own analogies about various physics concepts. Dunbar has shown that "if subjects generate their own analogies, they can find important structural features and relations in a concept." (Dunbar p.129). By using topics with which the students are already familiar, I should be able to get them to focus on the process of analogy making, and less on the content surrounding the source or target.

Objectives:

It is important that students be able to do the following:

1. Recognize the utility and develop the skill of making their own analogies when investigating new phenomena. Students should be continually be asking themselves "how is this LIKE things I have seen before and how is it DIFFERENT?." At one level this could be as simple as saying "this problem is a lot like the one we just did, except the numbers are different." At a deeper level this should be an ability to inventory one set of characteristics about a particular phenomenon and then find a different phenomenon that shares some of those characteristics. This corresponds to the TWA model's steps 1-4.
2. Identify the limitations of a model or an analogy (TWA step 6). Students must recognize that our words, drawings, calculations and mental pictures of natural phenomena are simply representations of reality and that there may be circumstances when the model does not match up with reality. Imagining a gas as a collection of zooming microscopic billiard balls may explain the pressure in a container, but will not allow you to predict that condensation will occur. You can calculate how far a grenade will travel before it explodes, but you cannot use the same techniques to calculate how far a muon will travel before it decays. In addition, students must recognize the limitations of certain analogies. Electron flow in a wire is like water flow in a pipe under some circumstances, but the analogy does not allow you to predict the magnetic field that surrounds the wire.

3. Students must be able to use analogies to gain insight into a natural phenomenon - particularly if the phenomenon has no valid conceptual model, but can only be analyzed mathematically (TWA step 4,5 and my added step 5A). This is the skill that this unit builds towards, for it is this ability that allows humans to work intuitively with otherwise incomprehensible phenomena: the wave-particle duality of light and matter, the effects of special relativity on space and time, and the concept of more than 3 spatial dimensions. It is not the goal of this unit that students be able to generate these altered meta-models on their own, because that would require that they be familiar with the natural phenomenon and perhaps even the mathematical models that are used to describe the phenomenon. But students should be aware of the fact that this is the only way that humans can comprehend certain features of our universe without the use of mathematics.

Strategies:

Students must first be aware of the fact that they use models to interpret and interact with reality. This can be achieved at the outset by asking how they can catch a ball flying through the air towards them. This is the most rudimentary conceptual model, where there is very little "translation" between reality and the language of the model. In fact, it may be hard for some students to even recognize the fact that there was any model generation at all. Next, students use basic numerical patterns to predict the structure of a simple machine. Students look through their textbook for examples of conceptual models or analogies and discuss what makes for a stronger/weaker model. Students will then examine the writings of some famous analogy makers, including Brian Greene, Michio Kaku and Richard Feynman, again looking for the use of conceptual models to help explain nature. Students then work on devising their own analogies for well studied phenomena, beginning with the conservation of momentum, and working up to more complex concepts, like field forces. Students are then introduced to some of the most famous analogies, dealing with phenomena that are beyond the scope of direct human imagination, beginning with the curvature of space-time due to the gravitational influence of mass. This analogy is teased apart, looking at how it takes a conceptual model (2-D objects in a 2-D universe, bent through 3-D space) and requires a mental shift in order to accurately represent the natural world (add a dimension, yielding 3-D objects in 3-D universe, bent through 4-D space).

Activities:

SECTION ONE: explicit discussion of mathematical models

Guiding questions:
-how do you know anything about the world around you?

-do you predict the future?
-how do you decide to act?
-what is learning?

Toss a roll of tape to a student (one who can see it coming and has a reasonable chance of reacting to it). Ask if the student knows the initial launch velocity, the initial launch angle, the height at the moment of release, the drag coefficient, the rate of rotation or the density of the air. Probably not. Yet in order to predict the position of that roll of tape after some elapsed time, all of those values (and more) would have to be considered. How is it possible to bring your hand to meet the tape without knowing all of those numbers? Humans are able to recreate the universe inside their heads, to a relatively high degree of accuracy. Define a model as a representation of reality or a concept that shares many characteristics with the entity modeled. Emphasize that our experiences in reality are mediated by models, some of which may be so familiar that you are unaware of their existence.

The models are what allow humans to predict the future. The more accurate the model, the more accurate our predictions. Throw a spinning index card to a student. Without a sufficiently developed model, predictions become much more inaccurate. When humans learn, we are simply revising models to more accurately reflect the way the world works. Discuss examples of learning in a more traditional sense and relate those definitions to a modification of the student's internal models.

Point out that some models are more complex than others, requiring the use of complex symbols to represent reality. Take out a box of staples and determine the number of staples in a single cartridge. These models, using a specified set of symbols and a particular group of operations on those symbols are what we call "math." Math has proven to be an extremely effective tool, allowing humans to make astoundingly accurate predictions about phenomena that take place far in the future.

Models must often be revised to correspond to reality or other accepted models. Use "happy" and "sad" bouncy balls to show that model revision will take place only when reality dictates that the model requires revision.
(Take out the bouncy ball (high coefficient of restitution) first and let it drop on a particular spot on a tile floor or desktop, distant from the students. Repeat about 8 times, each time asking students what they think will happen. They should be able to imagine the balls path very clearly. Ask a student to take out a pen or pencil, say some magic words and tap the ball gently. On the way back to the spot, replace the ball with a ball having a low coefficient of restitution and repeat the demonstration.)

Was the bounce “magically” removed from the ball?
What is a more likely explanation?
What was the model before? (The ball will return to a given height)
What is the model now? (The ball will return to a given height, if it is a particular ball)
What changed the model? (The presence of new data.)

Other models could involve measuring the heights, composition of the ball, the floor, the air, etc. Given sufficient data, we could generate an accurate predictor (model) for bounce height. The worth of the model is proportional to its predictive power, and the model’s agreement with other models. (Lack of correlation to other models is what rules out “magic”)

Using Interactive Physics, ask students to predict what the machine is that gives rise to the behavior of one bouncing circle. (Attach a circle element to a spring element, but do not show the spring.) Students should explain why they believe their answers are correct. Listen for models that correlate with the given data and other models.

SECTION TWO: Describing analogies and work with the 6 steps of TWA

Point out to students that a teacher's job is to take new ideas and connect them to student's prior knowledge so that the new concepts are understood in a meaningful context and are useful to the student. Often this can be accomplished by reminding students of situations with which they are already familiar, then drawing parallels to the new idea. Define an analogy: a set of connections between a familiar concept and an unfamiliar concept that provides insight into the nature of the unfamiliar concept. Give an example: when I first started teaching about velocity as the rate of change of displacement, I said that it was like how much money you made per hour. Go through the following steps, defining each one before continuing on:

1. define velocity as it appears in the textbook, without further explanation.
2. ask the students if anyone has a job, and if so, how much they make per hour.
3. point out that the hourly wage is, strictly speaking, the rate at which you gain money and takes the form of money/time. Your hourly wage can be used to determine the total amount of money earned in a certain time period, but is not the same as that amount of money ($7/hour for 10 hours amounts to $70 in earnings. However, $7/hour is not the same thing as $70). Remind students that a velocity is the rate at which an object changes its position, expressed as (change in position)/(time). The total change in position for a given time period can be determined, though this is a different type of quantity than the rate of change of position.

4. If you know how much a person earned and how much they make per hour, could you determine the amount of time they spent working? Go through the math to find this value. Use the analogy to determine the amount of time required to achieve a certain change in position, if the velocity is known. Deliberately show that it is the similarities between the relationships between the elements within the target and the analog that allow a deeper understanding of the target concept.
5. Ask the students to state additional ways in which there are similarities between velocity and an hourly wage. (examples include: commonly accepted time intervals for both quantities, use of negative values for rates, rates show change in values as opposed to totals with respect to arbitrary origins, etc)
6. Discuss ways in which a strict one-to-one mapping of wages to velocity would be an inaccurate way to conceptualize velocity (wrong units, accumulation of money as a physical entity, speed vs velocity distinction, difficulty in maintaining constant velocity in real-world circumstances, etc)

Ask the students to think of another analogy used by the teacher or the textbook in the physics class and go through a similar procedure, following the TWA steps and being explicit about the way in which the analogy is broken down into target, analog, relevant features, mapping similarities and identifying the ways in which the analogy fails.

SECTION THREE: students generate their own analogies

Review the concept of linear momentum. Ensure that students recall that it is not a directly measurable quantity like mass or length, but is a product of an object's mass and it's velocity; that momentum is a conserved quantity in the absence of external forces; that momentum conservation is an abstraction that can be used to determine the result of interactions between two or more objects, without resorting to the use of Newton's Laws. Ask students to do the following: make up a scenario that mimics the conservation of momentum in as many ways as possible. In other words, create an analog for momentum derived from a non-physics content area. The analog should be written out and the correspondences between the analog and the target should be made explicit. Students should then share their analogies with the class, and the strengths of each analogy discussed. Are there strong structural similarities between the analog and the target? Are there a large number of similarities, or just a few? Are there other elements of the analog that could distract a student from seeing the similarities? Point out how the discussion of the "best" analogy relates to the 6 steps of the TWA process.

SECTION FOUR: analysis of literature

Hand out copies of some popular science writing (such as Einstein's Universe, The Whole Shebang, The Hole in the Universe, Surely You're Joking Mr. Feynman, QED, A Brief History of Time, Chaos) and ask students to identify passages where the author has used an analogy to explain a concept. Again, go through the steps of analogy analysis, identifying the target, the analog, the salient features of both, mapping similarities, determining the applications of the analogy and discussing how the analog ultimately fails to map perfectly onto the target.

SECTION FIVE: using analogies to think about the unthinkable

Point out that in most cases a target concept is often new and perhaps more complex than the analog. However, there are some circumstances when the target is not comprehendible without the use of an analogy and not manipulable without a mathematical model. Offer Feynman's quote about the nature of reality: "The more you see how strangely Nature behaves, the harder it is to make a model that explains how even the simplest phenomena actually work. So theoretical physics has given up on that." (Haselhurst) Give the example of imagining 4-D space by using the analogy of a 2-D creature imagining 3-D space. Point out that it is ONLY through our use of the analogy that we humans can have any intuitive sense of 4-D space. Refer to Greene's similar strategy to introduce 4-D spacetime curvature in The Elegant Universe (Greene, p.67) and his later use of the garden hose analogy to discuss "curled up" dimensions (Greene, p.186). Point out his careful distinction between the target and the analog when discussing the "rubber sheet" analogy for gravitational attraction (Greene, p.71) Show how traditional analogies begin to fail when analyzing interactions that involve light. How fast does a light beam go through space? What if the light is emitted by a spaceship traveling near the speed of light? Point out that in many cases, our "intuition" about a situation is incorrect. Often this happens at small scales, large energies or high velocities – the realms of high-energy physics. Analogies with standard objects (without some sort of requisite twist) do not accurately model the actual behavior. Examine some of the analogies that have been used to describe these interesting phenomena:

Greene's odd landlord to explain away the ultraviolet catastrophe (in The Elegant Universe)

Feynman's clocks in photons to get around the wave-particle problem (in QED)

The bowling ball on a trampoline to describe Einstein's conceptualization of gravity as warped space-time.. (in Einstein's Universe)

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Content Standards:

Science & Technology Standards:
S1. All students explain how scientific principles of chemical, physical and biological phenomena have developed and relate them to the real-world situations.
S2. All students demonstrate knowledge of basic concepts and principles of physical, chemical, and biological and earth sciences.
S4. All students explain the relationships among science, technology and society.
S5. All students construct and evaluate scientific and technological systems using models to explain or predict results.
S6. All students develop and apply skills of observation, data collection, analysis, pattern recognition, prediction and scientific reasoning in designing and conducting experiments and solving technological problems.

Math Standards:
M1. All students use numbers, number systems, and equivalent forms (including numbers, words, objects and graphics) to represent theoretical and practical situations.
M4. All students formulate and solve problems and communicate the mathematical processes used and the reasons for using them.
M5. All students understand and apply basic concepts of algebra, geometry, probability and statistics to solve theoretical and practical problems.

M6. All students evaluate, infer, and draw appropriate conclusions from charts, tables and graphs, showing the relationships between data and real-world

Communication Standards:

C2. All students read and use a variety of methods to make sense of various kinds of complex texts.

C3. All students respond orally and in writing to information and ideas gained by reading narrative and informational texts and use the information and ideas to make decisions and solve problems.

C4. All students write for a variety of purposes, including to narrate, inform and persuade, in all subject areas.

C6. All students exchange information orally, including understanding and giving spoken instructions, asking and answering questions appropriately, and promoting effective group communications.

C7. All students compose and make oral presentations for each academic area of study that are designed to persuade, inform or describe