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ABSTRACT

Physics learning involves a change in the habitual perception of the everyday world. In order to describe the real world scientifically, an individual must develop perception and cognition capable of reconstructing the world from raw sensory data and incorporating acquired knowledge of the scientific community. The introductory physics student struggles to "see" the invisible filters of conventional physics ideas that most physicists take for granted. This paper draws on several theories of perception and imagery to explore experiences with the invisible world of physics. Discussion includes: generation of images as a route to understanding physics; internal physics imagery and physics thinking; viewing light as a particle or wave; the speed of light; and illustrating the speed of sound and black holes with visual metaphors. Nine figures illustrate various physics concepts. (Contains 11 references.) (AEF)

Perception In The Invisible World Of Physics

by Lisa Novemsky and Ronald Gautreau

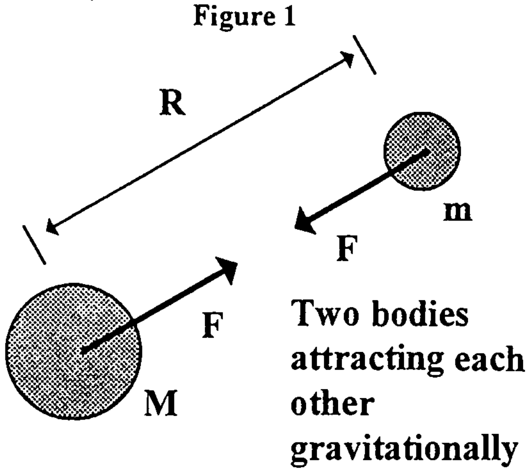
Abstract

We combine the knowledge and experience of a physicist, a relativist, who is a seasoned introductory physics professor, with the insight of a social psychologist and science education researcher, bringing the world of the psychology of perception to the task of exploring the world of physics imagery.

Visual Literacy for Basic Physics

At this very moment do you find yourself sitting down, sitting up, standing, lying, or floating around the room like an astronaut? Can you "see" the forces involved in shaping your position? Sir Isaac Newton pondered this question and was able to "see" the attractive force between bodies such as a falling apple and the earth. In 1696, he set forth his Law of Universal Gravitational Attraction that every body in the universe attracts every other body (Figure 1).

Figure 1



He went on to describe this relationship in a formal mathematical statement:

$$F = G\frac{Mm}{R^2}$$

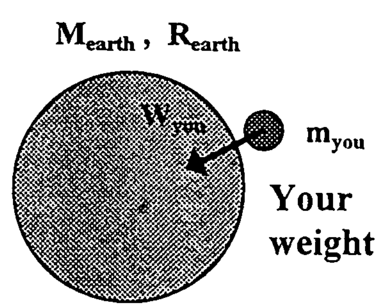
Here M and m are the masses of the two attracting bodies, R is the center-to-center distance between the bodies, and G is just a number that has the value $G = 6.67 \times 10^{-11}$ $N\text{-}m^2/kg^2$.

Think about the nature of communication of this formal physics equation. How does it differ from your internal image and the visual representation above? What is lost and what is gained in each of the three representations--the picture you formed in your mind's eye, the force picture above, and the mathematical equation?

Can you see that big earth below you with a very large mass M_{earth} pulling your little mass m_{you} toward its center a distance R_{earth} away from its center, as shown in Figure 2? This force, equal to your weight W_{you}, can be expressed in Newton's equation written to express your sitting on the earth's surface:

$$W_{you} = G\frac{M_{earth}m_{you}}{R^2_{earth}}$$

Figure 2



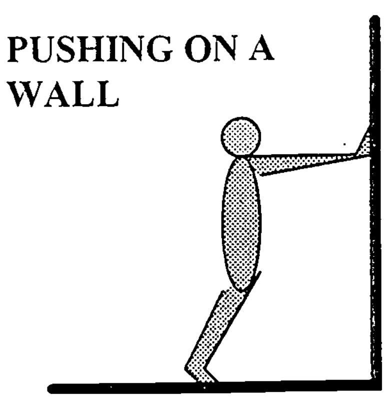
Can you picture the weight force on you? Force, one of the most basic concepts, inhabits the *invisible* world of physics.

Right now you are pulling on every thing else in the universe--the paper or book you may be reading, the earth below you, the moon above you, the farthest galaxy, the feathers of every bird. You are like an octopus possessing invisible tentacles that reach out and pull on every other object in the universe. To paraphrase an observation about gravity made by the eminent Nobel Laureate P.A.M. Dirac--a tiny flower fluttering in the wind shakes a star in a distant galaxy.

The Ubiquitous Force Vector

The gravitational force is a special force. It acts between objects that are separated from each other. The technical name is an "action-at-a-distance force." Other more "ordinary" forces occur, according to Newton, because one object touches another object. These are known as "contact forces." Push on a wall (Figure 3). Before you touch the wall, there is no force. According to Newton, only when you make contact with the wall does a force exists. Once you touch the wall, there is a force on it. In turn, there is also a force on your hand. You can feel it.

Figure 3

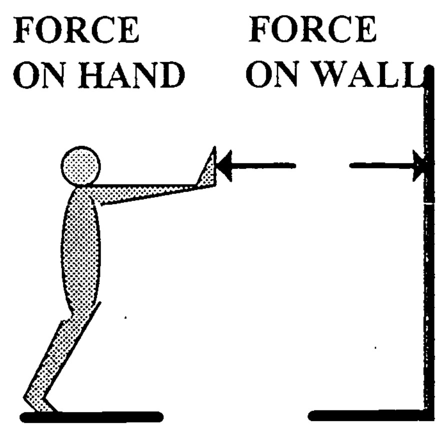


Before reading further, try to visualize the forces. What is it that you see in your mind's eye?

Now, let's look at how physicists describe the forces that arise as you push on the wall.

The contact force on the wall by you and the contact "back force" on your hand by the wall is an example of an action-reaction pair of forces. Newton tells us that forces always come in pairs--"action-reaction pairs." You will never find an isolated force. Moreover, at any given instant the strength of each force in the pair is the same (Figure 4).

Figure 4



In short, for every action there is an equal and opposite reaction. This is Newton's Third Law. Push on the wall with a force of five pounds, and the wall pushes back on your hand with a force of five pounds. Push harder with a force of ten pounds, and the wall pushes back on your hand with a force of ten pounds. No matter how hard or soft you push on the wall, the wall responds by pushing back on your hand with exactly the same force. If you don't push on the wall--if you are not touching the wall--then the wall is also not pushing on your hand, and you and the wall experience no force.

What do you actually *see* as you are pushing on the wall? Do you see your hand touching the wall, or the wall touching your hand? You don't see any arrows pointing one way or the other, as in Figure 4. You feel a force pushing harder and harder on your hand as you push harder and harder on the wall. These action-reaction forces are *felt* by you or the wall. But the forces are not *seen*.

Perceptual Aspects of Understanding Physics

The eyes of the physicist are tuned to the invisible. According to the physicist, everyday real world forces are seen as invisible pushes, pulls, tugs, heaves, squeezes, stretches, twists, and presses (Hart-Davis, 1989). The introductory physics student struggles to "see" these filters of conventional physics ideas that most physicists don't think twice about.

This paper draws on several theories of perception and imagery to explore experiences with the invisible world of physics. A basic process involved in the act of physics learning is a change in habitual perception of the everyday world. In order to describe the real world scientifically, an individual's perception and cognition must be capable of reconstructing the world from the raw sensory data perceived, incorporating the acquired knowledge of the scientific community. Understanding physics concepts involves the instantiation of a scientific mode of perceiving, categorizing, analyzing, and explaining the world. The development of an altered processing system for most of us involves a deep learning that encompasses multi-modal, socio-emotional, and language aspects. In order for an individual to be recognized as a physicist, that person is required to be somewhat fluent in scientific perception, analysis, and explanation.

Generation of Images as a Route to Understanding Physics

Albert Einstein is quoted as having said about his ability to conceptualize: "If I can't picture it, I can't understand it." Generating external images of physics phenomena by drawing, sketching, or diagram making can help the novice to create, refine, manipulate, and reason from internal visualizations. Dissonance created when comparing dissimilar representations provides the natural context for developing scientific understanding. Abstract representations and notations, such as the ubiquitous vector, play major roles in physics literacy. Graphic representations provide two dimensional concrete models for discussion and debate. Sketching may prove invaluable in self-generated explanations.

Internal Physics Imagery and Physics Thinking

Internal imagery seems to play a role in learning and memory that philosophers, psychologists, cognitive scientists, neuroscientists, and educationists have explored for centuries. Internal pictures, images, icons, diagrams, mental models, internal representations, and schema are among the constructs that exemplify theorists' efforts to describe the internal mode of representing, storing, imaging, and thinking about the external world.

"One of the remarkable attributes of human intelligence is the ability to convert a problem into a familiar form or *representation* that can be operated on using previously known techniques...(and) intelligence is largely the ability to create and manipulate descriptions" (Fischler & Firschein, 1987, p. 63). Howard Gardner defines spatial intelligence as the ability to form a mental model of a spatial world and to be able to maneuver and operate using that model (Gardner, 1987). Recent educational research indicates that this kind of intelligence is a skill that can be learned. Formerly it was believed that spatial ability was a facet of intelligence that was a stable measure for an individual.

Imagery can be "conceptualized metaphorically as a work space in which cognitive processes can operate" (Paivio, 1990, p. 74). This is particularly relevant to the process of problem solving, so prevalent in science, particularly in math and physics.

The famous examples in science of visual thinkers include the German chemist August Kekulé, who conceptualized the benzene ring. This crucial discovery was induced by a dream of a snake holding its tail in its mouth (Krippner, 1969). Richard Feynman is said to have been a visual thinker who drew "strange" diagrams on the blackboard which, with a minimum of equations, communicated his version of the universe (Dyson, 1979). Albert Einstein once wrote " The psychical entities which seem to serve as elements in thought are certain signs and more or less clear images which can be *voluntarily* produced and combined" (Ghiselin, 1952, p. 43).

What is light? Two Mutually Incommensurate Images

What could be more visible than light itself? The physics community has agreed to see light in two mutually incommensurate images. Light can be viewed as a wave or a particle. Scientific labeling justifies this indecisive set of "right" answers as the *wave-particle duality.* Within the world of physics the dichotomous metaphor of a single phenomenon is preserved. Sometimes physicists require light to be viewed as a wave, and at other times as a particle.

Light-- a Wave?

Light bends around objects, and interferes with itself producing intense and zero lines when it goes through a diffraction grating. The colors of the rainbow that result when light goes through a prism are understandable from the wave idea that light of different frequencies bends by different amounts as it moves through a dispersive medium. Experiments such as these gave rise to a wave picture of light.

As the wave picture of light developed, an important question arose. If light is a wave, what is it that is waving? The answer was provided in sorts by invoking the theory of electricity and magnetism that was developing in the 1800's, finally culminating around 1860 in the equations that Maxwell synthesized from work of many predecessors such as Coulomb, Gauss, Biot-Savart, Ampère, and Lenz.

The ultimate equations of electromagnetic theory realized by Maxwell are built upon the notion of a quantity called a *field*, an *electric field* **E** and a *magnetic field* **B**. These electromagnetic field quantities **E** and **B** are similar in sorts to the gravitational field force described above. It developed that the wave idea of light could be explained if light were supposed to consist of vibrations of electromagnetic fields. The feature that distinguishes light vibrations from other electromagnetic fields such as radio or TV waves is simply one of frequency--the number of vibrations per second of the field quantity.

As the theory of light as a vibration of an electromagnetic field began to take hold in the late 1800's, the relationship of the notion of the behavior of light as governed by Maxwell's equations given here could be summarized as:

And God said:

$$\oint \mathbf{E} \bullet d\mathbf{A} = q/\varepsilon_o$$

$$\oint \mathbf{B} \bullet d\mathbf{A} = 0$$

$$\oint \mathbf{E} \bullet d\mathbf{l} = -\frac{d\Phi_B}{dt}$$

$$\oint \mathbf{B} \bullet d\mathbf{l} = \mu_o \varepsilon_o \frac{d\Phi_E}{dt} + \mu_o i$$

AND THERE WAS LIGHT!!!

Light--A Particle?

The search for an understanding of the nature of light did not end here. In 1905, Einstein put forth two new views about light.

In explaining the photoelectric effect, Einstein showed that in certain instances light could not be a wave. Instead, light is composed of massless particles called photons. Photons, with zero mass, move at the speed of light. Further, each photon carries a bundle of energy E of the amount

$$E = h \times \text{(the photon's frequency)}$$

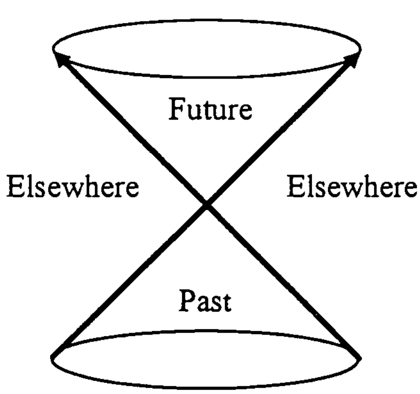
where h is a constant, called Planck's constant, whose numerical value is $h = 6.63 \times 10^{-34}$ J-s.

Light--The Ultimate Speed

Keeping the wave idea of light from Maxwell's equations, Einstein in 1905 showed in an entirely different paper putting forth his theory of special relativity that the speed of light was the *ultimate* speed. No particle with mass could be accelerated up to the speed of light.

The theory of special relativity led to the notion of an intertwined spacetime of the previously separated Newtonian picture of a separate space and a separate time. This brought into the mind's eye a new picture of light--the *light cone* (Figure 5).

Figure 5



At a given time at a given spatial location--at a given event--imagine that a flashbulb emits a flash of light. The equation of the light signal is

$$\text{distance} = ct,$$

where c is the speed of light, $c = 3 \times 10^{8}$ meters per second = 186,000 miles per second. That's really fast! On a plot of x and y versus t, with ct plotted vertically and x and y plotted horizontally, the resulting picture looks like a cone, as shown in Figure 5.

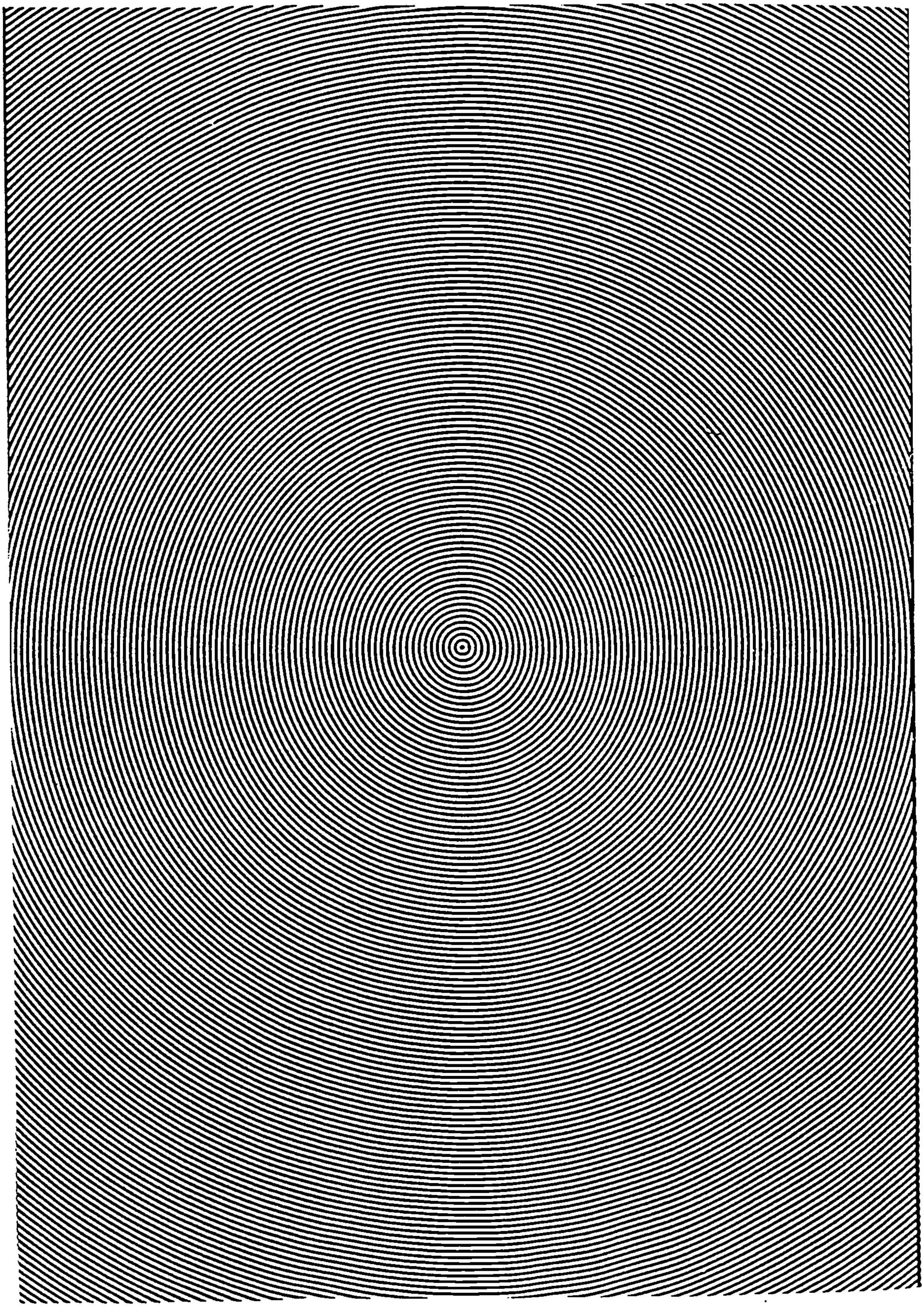
Making Sound Visible

Another wave phenomenon is sound. Sound travels in air via condensations and rarefactions of air molecules. But, have you ever seen an air molecule? It is possible to make this invisible vibration take on an apparent visible form.

Sound vibrations can be modeled with a common Slinky. The undulations of the coils of the Slinky provide a dynamic model of air molecules vibrating back and forth about their equilibrium position.

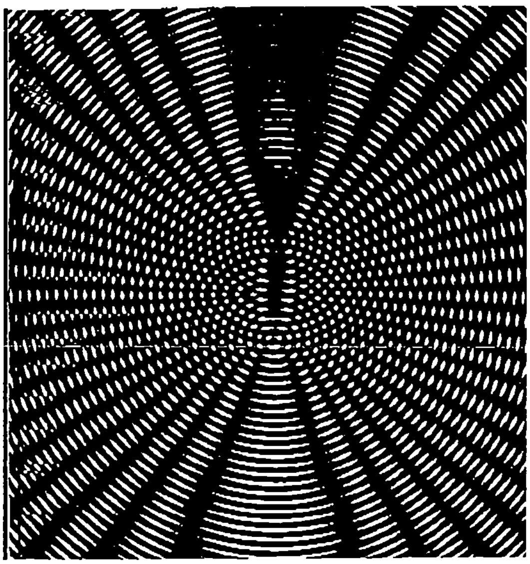
One can also model a periodically vibrating sound wave emitted from a point source with concentric circles, as shown in Figure 6, representing outward moving circular condensations and rarefactions of air molecules. If you make up two identical overhead transparencies from Figure 6, and place one on top of the other with the centers slightly offset from each other, you can see, and if you wish project through an overhead projector, a model of the interference lines that result from two sound sources of the same frequency, as shown in Figure 7. Further, if you make up two overhead transparencies that are slightly different in size, and place one on top of the other with the centers coinciding, you can project on a screen a model of the beats that result from two sound sources that differ slightly in frequency (and wavelength).

Figure 6



With a little practice, you can use various types of transparencies made from Figure 6 to experiment with visual versions of the invisible molecular motion as described by sound theory.

Figure 7



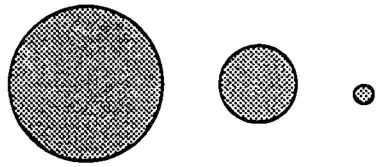
INTERFERENCE PATTERN FROM TWO SOUND SOURCES

Black Holes-The Ultimate Invisible

General relativity, developed by Einstein around 1915, is a theory of gravity that supersedes Newton's ideas and has important consequences for objects that are very massive. One of the notions that has emerged from the theory of general relativity is the possible existence of what has become popularly known as a *black hole*. Black holes are said to form when a star somewhat more massive than our Sun runs out of nuclear fuel and starts to collapse in on itself. If the process occurs in a proper spherical manner, the mass of the star doesn't change. Picture the radius of a spherical ball getting smaller and smaller while the mass stays fixed at the value it had when the collapse started (Figure 8).

Figure 8

GRAVITATIONAL COLLAPSE
Radius R decreases



Mass M stays constant

The collapse might stop, forming a very dense object such as a neutron star. On the other hand, some physicists believe that in some situations the process will not stop, but will continue indefinitely with the radius of the body approaching zero while its mass remains fixed. This means that the object's density--its mass divided by its spherical volume--gets larger and larger, approaching an infinite value as the volume shrinks to zero with the mass remaining fixed. Before the radius shrinks to zero, when an infinite density occurs, the radius will shrink through a critical value called the *Schwarzschild radius* R_S given by

$$R_S = \frac{2GM}{c^2}$$

Here M is the mass of the collapsing star. To get a feeling for how small this radius is for typical stars, the Schwarzschild radius for our Sun, whose mass is 2×10^{30} kg, is around 3 kilometers, around 2 miles, which is much much smaller than its normal radius of 7×10^5 kilometers.

The Schwarzschild radius is often referred to as the radius of a black hole. According to many present beliefs, once a star has collapsed to a radius smaller than its Schwarzschild radius, which is determined by its mass, it afterwards can never stop moving inward and must inevitably shrink to zero radius resulting in an infinitely dense object. As described in one widely-read tome on general relativity:

> "...the region r = 0 is a physical singularity of infinite tidal gravitational forces and infinite Riemann curvature. Any particle that falls into that singularity must be destroyed by those forces." (Misner, Thorne, and Wheeler, 1979)

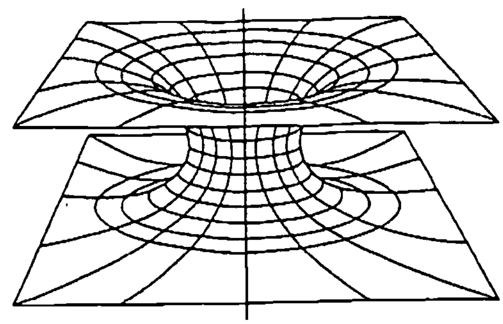
However, we who are outside the star's Schwarzschild radius will never see this happen. Once the star collapses within its Schwarzschild radius, nothing--not even light--can get out from inside the Schwarzschild radius. The star's mass is still tugging on us gravitationally, but we can see nothing that happens to the star when it is inside its Schwarzschild radius. A so-called black hole has been formed. The ultimate invisible object!

Visual Metaphor and the Marketing of Physics

This black hole scenario has been widely espoused and touted for a long time in arenas ranging from prestigious scientific journals to Reader's Digest, Walt Disney, and Star Trek. The arguments for the existence of black holes have been aided by the use of Madison Avenue-like words--black hole, white hole, worm hole, warped space-time--and eye-grabbing visuals such as shown in Figure 9. It is no wonder that the non-specialist audience accepts just about without question the validity of black holes.

However, some specialists who have some understanding of Einstein's theory of general relativity realize there is some shakiness in the foundation that holds up the popular edifice of black holes. Physical interpretations of the solutions of Einstein's mathematically complex field equations describing gravitational fields is far from trivial. In Newtonian physics there was no difficulty with the notions of space and time. Space was space, time was time, and that was it.

Figure 9



A WORMHOLE

It is important to understand--and this is usually not conveyed from specialists in physics theories to non-specialists--that the pictures resulting from mathematical equations in modern theories are not something that follow automatically like some God-given proclamation. In the end, in most modern physical theories the final (latest) visual representation results mostly from the minds of the persons who have come up with the most widely accepted interpretation.

The name "black hole" is a relatively recent terminology. The notion of the Schwarzschild radius was brought forth in 1916 when M. Schwarzschild solved exactly, for the case of spherical symmetry, the Einstein field equations, which were too complicated for Einstein, who came up with the theory a year earlier. Over the ensuing years, people wrestled with the interpretation of what happens around the Schwarzschild radius. It was not until the late 1960's that the visual metaphor "black hole" appeared in the literature. Now, black holes are everywhere, despite the lack of conclusive evidence. Because of what might be termed a "big noise approach," the intrinsically invisible black hole has become very visible in the minds of many.

It is important to realize that, in spite of what may be suggested in many writings, there has to date been no absolutely conclusive evidence that a black hole has been experimentally detected. Also, there exist viable alternative interpretations other than black holes to solutions to the Einstein field equations (Gautreau, 1995; Gautreau and Cohen, in press a,b).

The pro and con views of black holes can be aptly summed up in the words of the following bumper sticker.

BLACK HOLES SUCK!

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