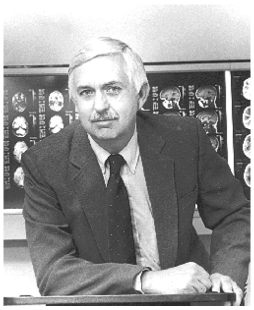
VISUALIZATION, IMAGINATION, AND THINKING *FROM EINSTEIN TO TEACHING MODERN PHYSICS*

P. Sprawls

Dept. Radiology and Imaging Sciences, Emory University and Sprawls Educational Foundation, www.sprawls.org



I. INTRODUCTION BY THE AUTHOR

As of the date of this publication, 2023, I have been a *physics teacher*--I prefer the term *educator*--over 60 years, first teaching general and nuclear physics before transitioning to medical physics, a specialization within the field of modern physics, for most of my career.

A major interest and effort throughout this period has been the development of concepts, methods, and resources to enhance the teaching and learning process in order to help learners/students develop a knowledge of physics that is of value in all aspects of their lives, especially professional activities such as the practice of medicine.

Visualization is a critical factor in learning physics to support many activities and is what we will explore here.

I began my physics teaching career, as I had been taught, in a classroom being lectured to along with a blackboard usually filled with equations. I soon began to realize that I was not providing my students with an opportunity to develop a knowledge of physics that would be useful to them both in everyday living and in their careers. This especially applied to those who were entering the medical profession. In essence, the traditional classroom was like a “box” in which we were enclosing our students, completely hiding them from the physical world they should be learning about. It occurred to me that physics classrooms needed “windows” or visuals through which the students could see the components of the physical universe they were studying, and the “teachers” could use their knowledge and experience to guide effective learning activities. A major effort of my career is producing “windows” or visuals and making them available to all physics educators, so that together, we can provide valuable learning opportunities for our students, as illustrated in Fig. 1.

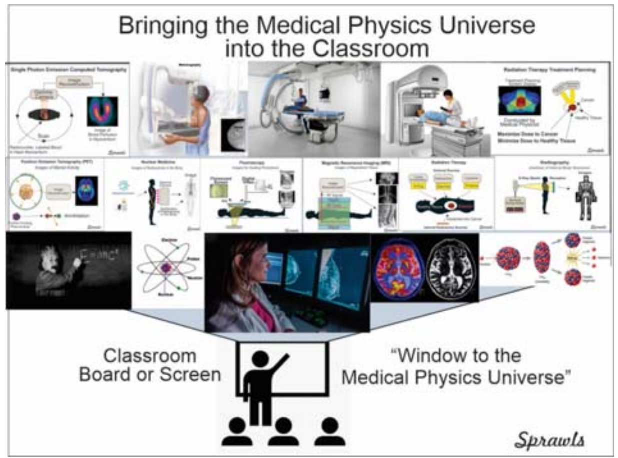


Fig.1. Classroom learning enhanced with visuals “windows” that bring the physical universe into the classroom for viewing and discussions.

Now, as we continue, I invite you to *think* along with me! Perhaps first, let us remember our experiences as students and how we were “taught” and what we learned. For those of us who are physics educators, we can use our knowledge and experience to help many others benefit from a knowledge of physics. There are also challenges.

The components or elements of the physical universe are of two forms with respect to human vision: they are either *visible* or *invisible*. Throughout much of history physics knowledge was limited to elements that could be sensed and interacted with using vision, hearing, or touch and feel. These were the physics areas of mechanics, optics, thermal, and acoustics. The fields of electricity and magnetism developed because of the observable effects they produced, including physical forces, visible light, and biological stimulation.

There were major components of the physical universe that were yet to be discovered and used in applications to benefit society. These were the several forms of *invisible* radiation and interactions with matter at the atomic level.

This invisibility not only delayed the discovery of these radiations but is also a continuing challenge in the effective teaching and learning of modern physics, especially the field of medical physics.

III. Learning physics

Learning physics--that is, the physical characteristic of the physical universe--is a natural human process that is continuing throughout our lives every day as we observe and interact with the physical environment around us. Learning the physics of water is an example illustrated in Fig. 2.

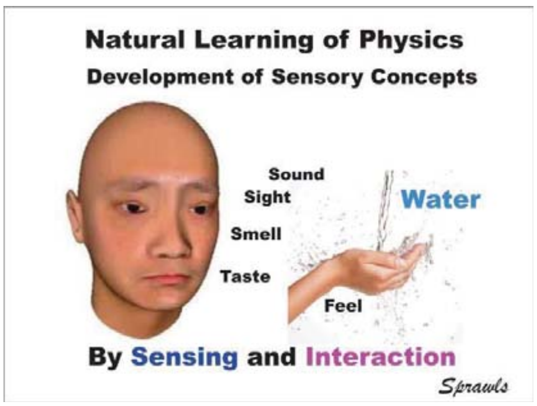


Fig. 2. Learning the physics of water.

IV. Sensory concepts

Let's think about how our knowledge of water is recorded in our brains. It is as images and sensations of water in many forms developed from our past experiences and observations, and interactions. We have visual images showing various characteristics, color, transparency, flow patterns, waves, etc. along with feeling characteristics, temperature, buoyancy, etc. This knowledge is a network of *sensory concepts* developed over time as we have experienced water and is illustrated in Fig. 3.

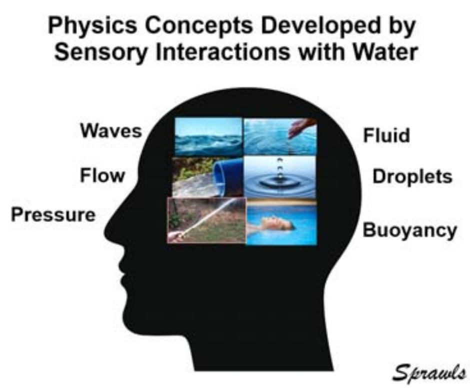


Fig. 3. The network of physics sensory concepts developed through seeing and interacting with water.

This is the physics knowledge that is necessary to guide our future interactions with water, from swimming in a river to preparing a cup of tea.

V. Symbolic representation of the physical universe

The physical universe can be described in two symbolic forms, *words,* and *mathematical symbols*. Words are used to provide definitions and verbal descriptions of objects, interactions, relationships, etc. Physics is a *quantitative* science with relationships described with mathematical symbols and equations.

This is the representation of the physical universe generally provided by textbooks and classroom lectures as shown in Fig. 4.

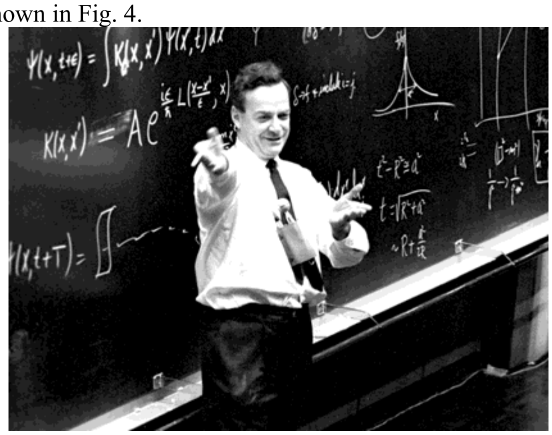


Fig. 4. Physicist Richard Feynman, famous for his creative lectures, combined spoken words and mathematical symbols on the blackboard to help students understand the quantitative relations in physics.

This is the method of teaching used in most academic physics courses for several reasons. It is the traditional form of physics education used over the years, and how we were taught. It is relatively efficient, not requiring extensive preparation of materials, especially classroom visuals or visible demonstrations. It is also easy to test with written examinations, both verbal and with mathematical problems to solve.

This type of teaching does not significantly contribute to the formation of *sensory concepts,* which is the knowledge that gives meaning to the symbolic knowledge using words and mathematical equations. Knowledge in the form of *sensory concepts* is of great value for physicists, engineers, etc. who also need the symbolic representations, especially mathematical equations. It is the physics knowledge *needed by everyone* to better understand the physical universe in which we live and do not need to know equations and make calculations.

Physics is one of the fundamental sciences of medicine. The human body is a physical universe itself filled with many forms of physical interactions and activity including force provided by muscles, the beating heart and associated blood flow, and electrical activity of the heart (EKG) and the brain (EEG). The medical field, physiology, is essentially the physics of the human body. An understanding of physiology as studied and applied by medical professionals is enhanced by an established knowledge of sensory physics concepts, for example, those related to fluids as illustrated in Figure 3. Those are concepts developed by observation and interaction with visible and touchable physical substances, i.e., water.

Many modern medical procedures, both diagnostic and therapeutic, use components of the physical universe that are *invisible*, including several forms of radiation, magnetic fields, and ultrasound. These are the medical specialties of Radiology/Roentgenology and Radiation Oncology/Therapy. For these specialties, physics is a required course in the Residency/Registrar programs for medical doctors and a significant part of the Board certifying examinations.

Medical Physicists are the educators who provide the courses, classes, and learning opportunities for these medical doctors, the Radiologists. A long-time and continuing challenge is helping radiology residents develop physics knowledge that will be of value in their future clinical activities and not just memorized materials to pass Certifying Board examinations.

The two types of physics knowledge for Radiologists and Radiology Residents, including how the knowledge is developed (learned) and used are illustrated in Fig. 5.

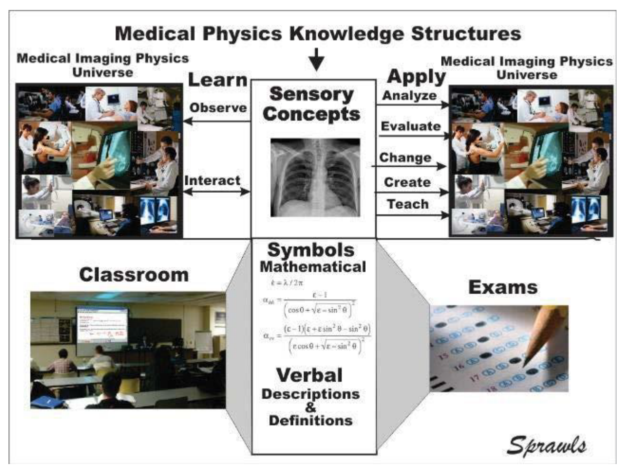


Fig. 5. Physics knowledge for Radiologists, both sensory concepts and symbolic representations.

The physics knowledge that is of the most value to the practice of Radiology and Medical Imaging is the network of *sensory concepts* that is developed through observation and experience, that is observing, interacting with, and applying it in clinical procedures. Also, in classes and conferences where the learning process is guided by an experienced "teacher" using appropriate images and visuals. These include concepts of both the visible and invisible components of the physical universe.

An example in which knowledge in the form of *visible physics concepts* is critical to the practice of Radiology and Medical Imagining is illustrated in Fig. 6.

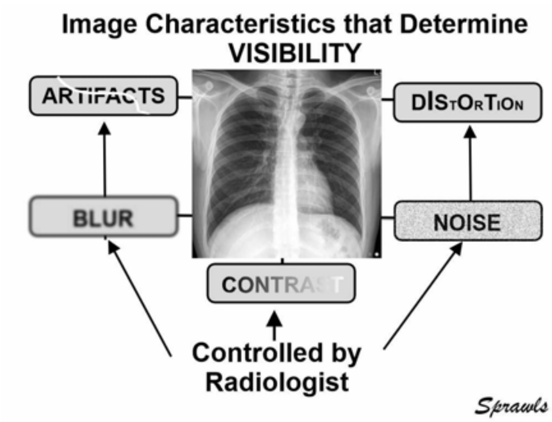


Fig. 6. The physical characteristics of medical images that collectively determine visibility of specific objects and conditions within the human body.

A medical image is a physical object with specific characteristics associated with it. These characteristics can be represented symbolically with both *words* (definitions and descriptions) and *mathematical symbols* and *equations* (quantities and relationships). These are the representations that are often the easiest to "teach" and test on examinations, but not the knowledge to support clinical applications.

Effective application of physics principles to control and optimize medical imaging procedures requires the ability to *visualize* these characteristics and their effects on visibility of objects within the human body in relationship to the object's physical characteristics. It requires sensory/visual concepts of each characteristic and the factors that control them.

VI. THE VALUE OF KNOWLEDGE TYPES

The two types of knowledge, or representations of the physical universe, each has value relating to how it is to be used. An example is illustrated in Fig. 7.

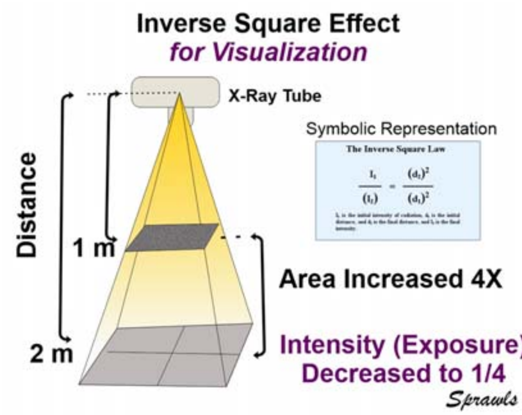


Fig. 7. The representation of the inverse-square law both visually and symbolically.

X-ray beams as used in medical imaging follow the inverse-square law with the intensity (radiation exposure or dose) decreasing with distance from the source.as seen here.

The medical doctors--the Radiologists-- and the technologists conducting the imaging procedures--the Radiographers--need an understanding of this effect for setting up and adjusting the imaging procedures and for radiation safety considerations. This is conceptual knowledge and the ability to *visualize* the characteristics of the x-ray beam as illustrated above.

Physicists also need the conceptual knowledge but also the symbolic representation (mathematical equations) for the purpose of calculating intensity (exposure, dose) values at various distances from the source of the radiation.

VII. VISUALIZATION AND IMAGINATION

Both the formation and use of sensory concepts requires the *process of visualization.* Visualization is the process of forming visible images in the brain and is a major form of human learning. Many--perhaps most--of our memories from throughout our lives are in the form of images that we can recall and "see" again. These mental images were formed as we viewed and interacted with actual physical items and activities and are a continuing process. For example, today, we can visualize much of what we saw yesterday, and other days in the past.

Imagination is the act or power of forming mental images of or visualizing something that we have never viewed. It is a very important form of thinking in the process of developing solutions to problems and creating new things. It is visualizing what can be, at least in our minds.

A network of *visual concepts* in the brain provides a foundation for *imagining* new and valuable possibilities that does not come from a knowledge consisting of memorized facts and symbolic representations.

VIII. Einstein on visualization, imagination, and thinking

Albert Einstein, the highly intelligent physicist who made major discoveries including several forms of relativity, the photo-electric effect, etc., was a visual thinker. His interest was in visualizing and thinking about factors that were not visible to the human eye--the invisible components of the physical universe. It appears he first developed theories with visualization and imagination (mental experiments) and later developed the mathematical expressions. This is emphasized in two of his quotes:

"*Visualization* is More Important Than Knowledge
Imagination is Everything. It Is the Preview of Life's
Coming Attractions"

One of the most popular stories is about his riding on a beam of light and wondering about the effect on visibility, like looking at himself in a mirror. One of the many illustrations of this is in Fig. 8.

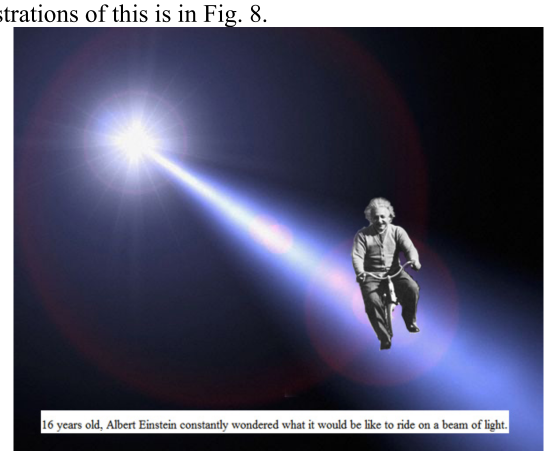


Fig.8.Einstein riding on a beam of light…in his imagination.

In addition to his many discoveries and developments in physics, his perspective on physics education provides guidance for effective educational methods that we can use now. Two of his thoughts are illustrated in Fig. 9.

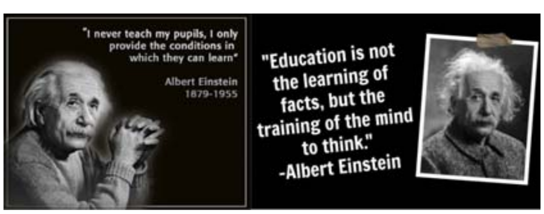


Figure 9. Einstein's thoughts on physics education.

IX. Thinking

The use of physics knowledge in virtually all applications ranging from preparing a cup of hot tea to developing and using advanced medical imaging procedures requires *thinking.* That is the mental process used to define and organize experiences, plan, learn, reflect, and create.

Let's do a brief experiment by *thinking* about the food, pizza. What comes to your mind? Generally, images of round pizzas with your favorite toppings along with memories of taste and smell, the sensory concept of pizza that has developed over the years. As we *think* we can plan on what flavor of pizza we would like to have the next time.

Productive thinking and planning require the ability to visualize objects, conditions, relationships, etc. as we have just done for pizza. A mental network of sensory concepts, especially visual, provides the foundation of productive thinking as illustrated in Fig. 10.

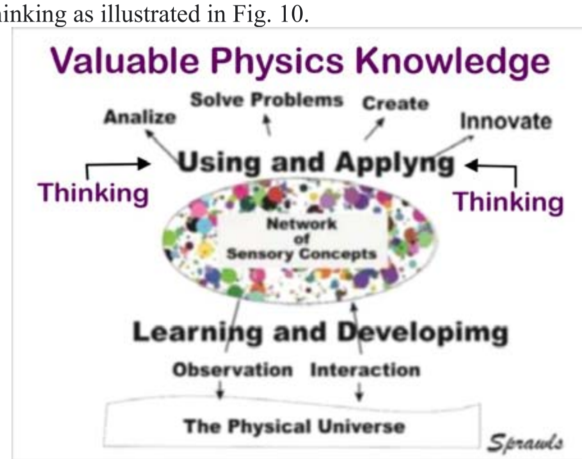


Fig. 10. Physics knowledge that enables thinking and useful applications.

Training a mind to think, as expressed by Dr. Einstein, first requires a collective knowledge of things (objects, relationships, characteristics, etc.) to think about. A major function of physics education is providing conditions in which "pupils", students, or learners, can learn by observing and interacting with the physical universe as we have learned the physics of water. The challenge is visualizing and interacting with the invisible components of the physical universe, especially the radiations and associated interactions.

In learning laboratory and practical experiences, we can measure the quantitative characteristics of radiation (air KERMA, penetration, etc.) which is a valuable learning experience that can be applied later in professional physics activities including radiation therapy treatment planning and optimizing medical imaging procedures. This does not? provide a comprehensive conceptual knowledge of radiation that can be the foundation for productive thinking as described above.

Perhaps this is what we can learn from Prof. Einstein: learning physics is a natural human process, and the role of educators, "teachers", is to provide conditions in which pupils can learn, using visualization, imagination, and thinking.

X. THE VALUE OF VISUALIZATION AND IMAGINATION IN MODERN PHYSICS

As we are exploring here, the physical universe consists of both visible components (water is the example we are using) and invisible, including several forms of radiation, magnetic fields, and the interactions of radiation with matter at the atomic and nuclear levels.

If we can "see" or visualize radiation as we can substances like water, it then becomes possible to develop sensory concepts that enables thinking that can be used to support many productive activities and possible innovations.

The physics of x-ray imaging in medicine is one of the Author's special interests. The physical elements of this component of the physical universe are all invisible as illustrated in Fig. 11.

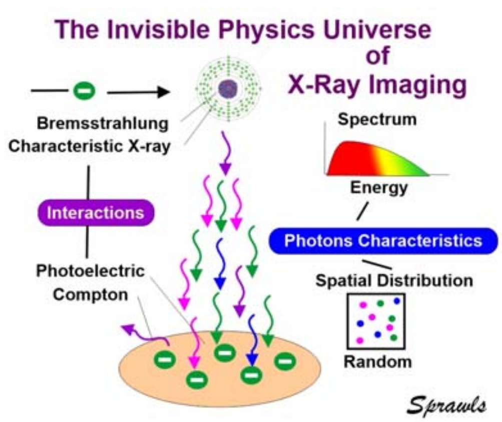


Fig. 11. The invisible physical elements of the x-ray imaging process.

Let's compare this to Fig. 2. That was illustrating how we learn the physics of water through visualization and other sensory interactions. We do not have the same opportunity for learning the physics of x-radiation which is completely invisible.

XI. TEACHING MODERN PHYSICS

We cannot effectively teach modern physics--x-ray imaging is our focus here--by lecturing and telling learners what we know. We can teach the quantitative and mathematical relationships but that does not contribute to the formation of visual images and concepts that can be a foundation knowledge for productive applications and innovations.

XII. EFFECTIVE LEARNING AND TEACHING

In the context of our thinking here, *effective learning* is the process of developing knowledge that can be used and applied for productive purposes as illustrated in Figure 10.

My perspective of *effective teaching* is the combination of providing pupils with the opportunity to learn (especially visualization and mental interaction) as expressed by Dr. Einstein and then a learning facilitator (teacher) helping the pupils to learn. This can be by using their knowledge and experience to guide and enhance the learning process as illustrated in Fig. 12.

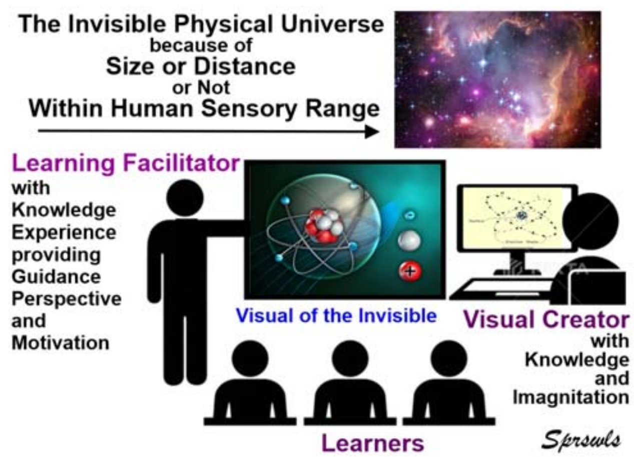


Fig. 12. An effective learning environment for developing conceptual knowledge of the invisible components of the physical universe.

XIII. VISUALIZING THE INVISIBLE

It has been suggested that perhaps 99% of the physical universe is invisible to humans because of factors identified in Fig. 12. Visibility of some has been achieved with the development of instruments including microscopes (size) and telescopes (distance) but physical objects that are not within the human sensory (especially vision) remain a challenge. It is the ability to visualize these that enables the development of sensory concepts that is the foundation for valuable applications (analyze, problem solving, create, innovate, etc.) as illustrated in Fig. 10.

What is needed is the ability to visualize these objects, their characteristics, and their physical interactions.

XIV. The visual creator

Creating visual representations of the invisible elements of the physical universe requires *imagination*. That is the ability to use accumulated knowledge, especially that developed from personal experience and observation, and think how the objects, characteristics, interaction, etc. can be represented in a visual form.

An effective visual creator is a physicist who "has this talent" just as effective writers and authors provide good written descriptions, as in most textbooks.

The general function of a visual creator is illustrated in Fig. 13.

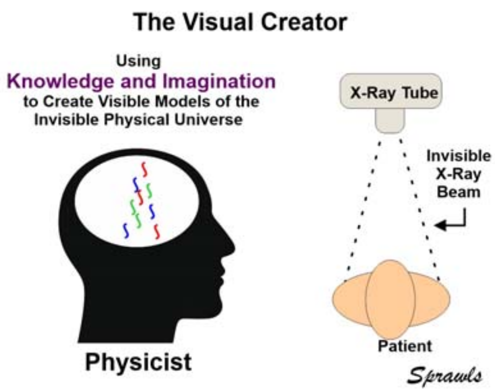


Fig. 13. Creating visuals of the invisible.

Creating conditions in which "pupils" can learn physics, as described by Dr. Einstein, is a collaborative effort by textbook authors, classroom learning facilitators (teachers), student laboratory instructors, and *visual creators*. Visuals (illustrations, diagrams, pictures, etc.) have been a valuable element in physics education in textbooks and class presentations and discussions.

Here we distinguish between a *visual creator* and others who produce illustrations, diagrams, pictures, etc. of visible objects or systems that are also valuable in the learning process by helping learners visualize components of the physical universe.

A *visual creator* must use their *imagination* to produce visible representations of invisible objects along with their characteristics, relationships, and interactions. It generally requires an understanding of the physical principles, laws, and quantitative (equations) relationships as the foundation knowledge to work with.

Creating and publishing visuals (from one to many) that can be used to help learners visualize components of the physical universe, an x-ray beam is an example, is an opportunity for physicists to receive recognition and contribute to and educational process around the world. Fig. 14 is a composite of several visuals created by the Author and are available, along with many others at: www.sprawls.org/resources .

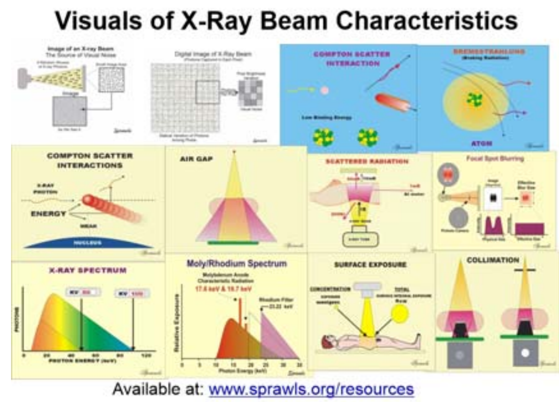


Fig. 14. Selected visuals provided by the Author illustrating the many, generally invisible, characteristics of an x-ray beam.

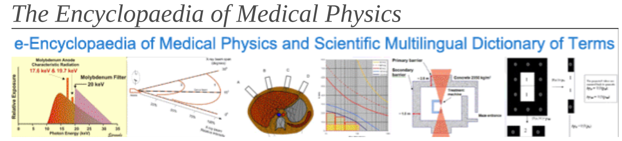
Visuals as shown here, enable learners to visualize and develop conceptual knowledge of the many characteristics and relationships of x-radiation. This is the type of physics knowledge that supports clinical applications.

XV. Sources of visuals for learning and teaching

The internet and World Wide Web (WWW) is a vast source of visuals that are valuable for physics learning activities. The interest here is specifically for the field of medical physics.

The visuals can be found and downloaded through the following websites.

The Encyclopaedia of Medical Physics



This is an extensive on-line open resource (free of charge) with articles on virtually every medical physics topic including images and visuals.
These are available at:
http://www.emitel2.eu/emitwwwsql/encyclopedia.aspx

The Sprawls Resources

The Resources is a collection of textbooks and modules created by the Author with an emphasis on images and visuals that can be used in class or conference presentations and discussions.
These are available at: www.sprawls.org/resources .

Google Images

Google Images

This is a search program for finding images/visuals on the internet by a specific topic. It is available at: https://images.google.com/

Here is an example. Searching on the term, "x-ray sprawls" finds the images shown here: x-ray sprawls - Google Search

XVI. Summary and overview

As emphasized by Professor Einstein, *visualization* and *imagination* are critical functions in learning physics and applying it in creative activities. Learning physics is an ongoing natural human function as we observe and interact with the physical universe around us developing a network of sensory concepts that provide a foundation for *thinking*. Physics courses in academic institutions provide a symbolic and more quantitative representation of the physical universe in the form of words (definitions and descriptions) and mathematical symbols (quantities and relationships). Both *conceptual* and *symbolic knowledge* are valuable, depending on the needs of the learner with respect to applications, both in daily living and professionally, especially in the practice of medicine.

A specific challenge in some fields of physics education, especially medical physics, is providing opportunities for learners to visualize the invisible components of the physical universe, especially radiation.

Physicists, especially those with experience and imagination, can contribute to medical physics education around the world by creating and sharing visuals over the internet that enable others to *visualize*, *imagine*, and *think* productively about physics.

XVII. The author

Perry Sprawls, Ph.D., FAAPM, FACR, FIOMP, FIUPESM, is a clinical medical physicist specializing in medical imaging and diagnostic radiology and in education. He is Distinguished Emeritus Professor at Emory University School of Medicine in Atlanta and has served as Co-Director of the College on Medical Physics at the ICTP in Trieste. He contributes to medical physics education around the world through the Sprawls Educational Foundation, www.sprawls.org. It is the combination of his experience as a clinical physicist and educator that is the foundation for developing and sharing resources to support the teaching of medical physics. His continuing research and development activities are resulting in models for increasing the effectiveness of both the learning and teaching process, especially for clinically applied medical physics. This can be reviewed in the Bibliography.

Contact with the corresponding author:
Prof. Perry Sprawls
Email: sprawls@emory.edu

XVIII. Bibliography

The publications provided here are devoted to two specific but related issues in medical physics education. One is the factors that determine the effectiveness of educational activities to support clinical applications. The other is the application of specific learning and teaching principles in the optimization of medical imaging procedures.

EFFECTIVE PHYSICS EDUCATION FOR OPTIMIZING CT IMAGE QUALITY AND DOSE MANAGEMENT WITH OPEN ACCESS RESOURCES
. P. Sprawls1, P-A. T. Duong, MEDICAL PHYSICS INTERNATIONAL Journal, vol.1, No.1, 2013
http://www.mpijournal.org/pdf/2013-01/MPI-2013-01-p046.pdf

PHYSICS EDUCATION FOR THE OPTIMIZATION OF MRI CLINICAL PROCEDURES: VISUALIZING THE INVISIBLE AND COLLABORATIVE TEACHING
P. Sprawls. MEDICAL PHYSICS INTERNATIONAL Journal, vol.1, No.2, 2013
http://www.mpijournal.org/pdf/2013-02/MPI-2013-02-p134.pdf

OPTIMIZING MEDICAL IMAGE CONTRAST, DETAIL AND NOISE IN THE DIGITAL ERA.
P. Sprawls. MEDICAL PHYSICS INTERNATIONAL Journal, vol.2, No.1, 2014
http://www.mpijournal.org/pdf/2014-01/MPI-2014-01-p041.pdf

EDUCATION MODELS FOR THE EXPANDING ROLE OF CLINICAL MEDICAL PHYSICS.
P. Sprawls. MEDICAL PHYSICS INTERNATIONAL Journal, vol.5, No.2, 2017
http://www.mpijournal.org/pdf/2017-02/MPI-2017-02-p167.pdf

DEVELOPING EFFECTIVE MENTAL KNOWLEDGE STRUCTURES FOR MEDICAL PHYSICS APPLICATIONS**.**
P. Sprawls, MEDICAL PHYSICS INTERNATIONAL Journal, vol.6, No.1, 2018
http://www.mpijournal.org/pdf/2018-01/MPI-2018-01-p128.pdf

DIGITAL ELEMENTS, IMAGE QUALITY, RADIATION EXPOSURE, AND PROCEDURE **OPTIMIZATION**.
P. Sprawls. MEDICAL PHYSICS INTERNATIONAL Journal, vol.6, No.2, 2018
http://www.mpijournal.org/pdf/2018-02/MPI-2018-02-p255.pdf

EFFECTIVE PHYSICS KNOWLEDGE FOR DIAGNOSTIC RADIOLOGISTS
P. Sprawls. MEDICAL PHYSICS INTERNATIONAL Journal, vol.7, No.3, 2019
http://www.mpijournal.org/pdf/2019-03/MPI-2019-03-p257.pdf

ENHANCING MEDICAL PHYSICS TEACHING WITH IMAGE REPOSITORIES AND SHARED RESOURCES
P. Sprawls. MEDICAL PHYSICS INTERNATIONAL Journal, vol.8, No.3, 2020
http://www.mpijournal.org/pdf/2020-03/MPI-2020-03-p479.pdf

MAPS FOR DEVELOPING MEDICAL PHYSICS CONCEPT NETWORKS IN THE MIND P. Sprawls
MEDICAL PHYSICS INTERNATIONAL Journal, vol.10, No.1, 2022
http://www.mpijournal.org/pdf/2022-01/MPI-2022-01-p019.pdf