Playing With Gravity, Einstein's Happiest Idea

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The outlined lesson plan shows (A) some general and specific steps that Albert Einstein used to hypothesize, formulate and construct one of his famous models (the gravitational redshift), and (B) the way the model was verified using the Mossbauer effect. Both parts make use of the Doppler effect as prior knowledge. Einstein's famous free-fall thought experiment is discussed, and explained using analogous demonstrations that involve minds-on and hands-on Project Based Learning (PBL). It is hoped that this contribution can lead to a Cognitive Laboratory of Operational Experiments (CLOE) on gravity for older children, to introduce them to modern research, and provide a key example for the use of meta-cognition meta-models to help develop creative relationships with models and modeling. PBL is used to help introduce the students to the Mossbauer effect.

1 The Doppler Effect in Developing the Gravitational Redshift Prediction

While playing with the idea of gravity, by means of thought experiments, Einstein (Nobel laureate 1921) constructed an amazing model that predicts the gravitational redshift, i.e., that light changes its frequency when it propagates against gravitational field. The process or method used is an example of how model construction is guided by general ideas, meta-cognition, or meta-models of reality. It takes several distinct, steps discussed below. First, Einstein did some thought experiments that might model gravity. This lead to his "happiest idea", "*In free-fall, a person cannot feel their own weight*".

TeamWork Project 1 The CLOE on gravity[1,2] provides a wealth of insights as well as of references about gravity conceptions of students aged 6 to 10. It might benefit older students, especially if they happen to be challenged about gravity and need more demonstrations and discussions that show the free-fall idea both in the physics classroom and outside it. E.g., pierce a plastic bottle with a small hole near the bottom, fill it with water, and let the bottle drop in free-fall. While in free-fall, the water does not leak out. Many easy variations on this experiment exist. Design some free-fall experiments using the idea suggested by the above example. E.g., use a rubber band or a magnet which barely fails to hold up a weight while stationary. Sketch the idea and materials that you need and get the teacher's approval to proceed. They all make use of the fact that the internal stress and strain forces in a small freely falling object cannot include any significantly strong forces due to the pull of gravity. Is every satelite, like the moon or the International Space Station, ISS, in continuous free-fall?

Extra credit, Choose one or both of the following: (A) using the WEB for "starters", design a 3 or 4 meter high free-fall tower with a movie camera to record the phenomena. Do experiments. (B)Ask the management of a tall modern building for permission for your school group to use the elevator to perform a fun experiment to model the acceleration of an elevator as it moves from floor to floor by using a portable weight scale to obtain intereresting graphs. How does the elevator's acceleration and speed affect the graphs? How does swinging pendulum behave in the elevator/ in free-fall?

Team Work Project 2: Still being at the very early stages of exploring space, we are doing varied microgravitational experiments in many contexts such as in the International Space Station (ISS), (which is in continuous free-fall), in free-fall towers (where objects are dropt long distances in vacuum and studied), and various "vomit comets" (These are structurally beefed-up airplanes that can safely negotiate very high altitude parabolic trajectories where free-fall is experienced for a few seconds). Perform a WEB quest [4] to describe microgravity/free-fall experiments and facilities. What sort of phenomena will change in low gravity? E.g., how does a flame look without convection currents?

Extra Credit Do a WEB quest to search for gravitational waves and observatories, (LIGO and LISA). They are not directional . Why? How can we use triangulation from separate observatories to calculate their direction? LISA, is the 5 million km long space-based gravitational wave observatory currently being planned for operation in ten years time. Why must they be so sensitive to detect the waves? Why is the Doppler effect used to make corrections for the Earth's daily and yearly motions?

After his happiest idea about free-fall, Einstein asked many questions, such as, *How can I use this? What does this imply? How can I explain this fully?*, He formulated what is now known as the *Einstein equivalence principle*, "At a "very small" local level[1] one cannot tell the difference between forces due acceleration F= ma, or to a gravity field, F =mg by any mechanical or electromagnetic experiment."

See [3] for more details. This key principle guided his model construction. E.g., one of his answers to "*So what? What next?*" was the prediction of the gravitational redshift by placing two major ideas (the Einstein equivalence principle and the Doppler effect) in juxtaposition. The step by step thinking/modeling probably occured as follows:-

a. Given prior knowledge: When moving away from a light source, experimental evidence shows that the observed frequency is down-shifted (redshifted) according to the Doppler effect equations, just like the sound of a receding ambulance is down-shifted more if the ambulance is traveling faster away from the observer. I.e., the larger the velocity, the more the redshift.

b. Hence, by the principle of equivalence, when light travels up (down) a gravitational potential well its frequency and energy decrease (increase) in proportion to the steepness of the walls

This major conclusion still appears as a little startling, but Einstein boldly continued the steps. He constructed a theoretical quantitative model that predicts exactly what this gravitational redshift is. The next step was to verify that the predictions made by the thought experiment are indeed the case.

2 Using Doppler And Mossbauer Effects to Verify Gravitational Redshift Model

Einstein's predictive model was verified using the Doppler effect experimentaly in 1959 [5] within a 22.6 meter tower on the campus of Harvard University by using the then brand new technique of Mossbauer (Nobel laureate 1961) spectroscopy. Atoms of the Iron Fe 57 isotope were placed into a crystal fixture and used to radiate 14.4keV Gamma ray photons that were directed from the bottom of the tower to the top of the tower. The gamma rays were not absorbed by an identical crystal fixture at the top of the tower because they were redshifted as predicted by Einstein. The Doppler effect and the Mossbauser effect were used to show that the amount of redshift was equal within ten % (now one %) of that quatitatively predicted. The Doppler shift can be caused by wiggling either the receiving or the transmitting crystal by a precisely controled motor to very precisely measure and control the velocity of the fixture of the crystal E.g., if the receiving crystal is wiggled, then when the velocity is just right in the downward direction, the Doppler effect ensures that a blueshift occurs "for the detector", the "lost" frequency and energy are regained in the detecting process, and the photon is absorbed by the detecting crystal. Conversely, if the source is wiggled and moving upward, the blueshifted photon loses the additional energy as it travels upward. I.e., at just the right velocity as predicted, the gamma rays are absorbed. See [5] for more details. Note: Rudolf L Mossbauer (Nobel laureate 1957) discovered a method for obtaining photons from a crystal with a very narrow frequency band [6,7] by quantum transitions of atomic nuclei. Very tight precision is needed because in the 22.5 meter journey, the frequency changes very slightly. So the original frequency must be known within even tighter limits.

Team Work Project3 Design and build (or otherwise obtain) a wooden cart with a spring powered ball-bearing gun mounted on it. Obtain a set of weights to place on the cart and do experiments varying the amount of weight on the cart. Measure the recoil force and velocities. As more weight is placed on the cart, the less it recoils. Explain why this is so. How does this relate to the Mossbauer effect?

References

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[1] I.e., in a very small (infinitesimal) neighborhood around the sensing equipment. Also, a large enough body can be subject to variations of the gravitational field strength of a strongly varying field. This difference in effects provides an opportunity to measure a distinct difference between gravity and "pure" constant acceleration in a flat space.