A Black Hole in the Living Room

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We present a novel approach for studying a curved spacetime in a holistic, but still intuitive way. Using this approach, laymen and newcomers have a way to comprehend the properties of curved space without knowledge of the abstract mathematical formalism of non-euclidean spaces. This technique allows to demonstrate various phenomena observable in astronomy by means of familiar objects. We focus on the spacetime of a static black hole as the most prominent and easiest solution from general relativity. As the theory of general relativity is a theory of geometry, it is representable by geometrical means, i.e. without the overhead of abstract mathematics.

The mathematical description of a static black hole is given by the so-called Schwarzschild metric, which describes the relationship of infinitesimal distances and is usually written as

$$ds^2 = (1 - \frac{2m}{r})dt^2 - \frac{1}{1-\frac{2m}{r}}dr^2 - r^2 d\vartheta^2 - r^2 \sin^2\vartheta d\varphi^2 \quad . \qquad (1)$$

using spherical coordinates t, r, ϑ, φ and with m the mass of the black hole.

We construct a virtual scene similarly to [1,2,3], but more complex, based on [4], utilizing intuitively recognizable objects: a large plane serving as "base", some cylinders with some visually interesting features, and an icosahedron placed on a desk, which periodically blinks in intense red light. By introducing a finite speed of light (still in Newtonian physics, with no relativity involved at all) we are able to depict propagating wave fronts of light, see Fig. 1.

In a curved spacetime light is attracted by masses similar to planets and comets traversing in the solar system. Such curved paths of light rays allow us to see a certain object multiple times, an effect well known in observational astronomy as "gravitational lensing" (see also [5]). Beyond multiple appearance of an object, curved spacetime also provides different perspectives: In the case of the desk that our icosahedron is resting on, the primary image (Fig. 2, right) displays the side view, while the secondary image shows the upper surface (Fig. 2, left). Note that the images in Fig. 2 are not to scale. Actually, the secondary image is much smaller than the primary one. Using our intuition from flat space, this can be interpreted as the secondary image being further away than the primary one. The ability to employ a stereographic display fully supports this finding even for viewers without a-priori knowledge of relativity and curved spacetime. This effect is a direct visualization the *spatial* components of the Schwarzschild metric eqn. (1).

The blinking light source introduces a dynamical component in the scene which allows us to also depict the time delay of secondary images, see Fig. 3.

This is known as the Shapiro effect [6] and has been observed in nature in great precision. This indicates that the visual (proper) distance of the secondary image is equal to the proper distance of the brick cylinder, i.e. it looks further away than the primary image. Stereographic real-time display of pre-rendered frames supports this impression and was successfully demonstrated to unprejudiced spectators [7]. Due to the time dilation in a gravitational field, wave fronts of light pulses will thus "pile up" at the horizon: a (static) membrane enveloping the black hole just outside the horizon will reflect pulses in the past as well as recent ones, as depicted in Fig. 4. This effect is measurable and observable as redshift of light, but our approach provides a visualization that is alternative to shifting the colors (e.g. such as in [8]). The dynamic component of the blinking light provides a direct visualization of *time* component of the Schwarzschild metric eqn. 1.

The tool used in our work is the `Light++` raytracer [9] with its extension to general relativity. This research employed the resources of the Center for Computation and Technology at Louisiana State University, which is supported by funding from the Louisiana legislature's Information Technology Initiative. This work was partially supported by the NSF under grant PHY0505761 and by the National Center for Supercomputer Applications under grant MCA02N014.

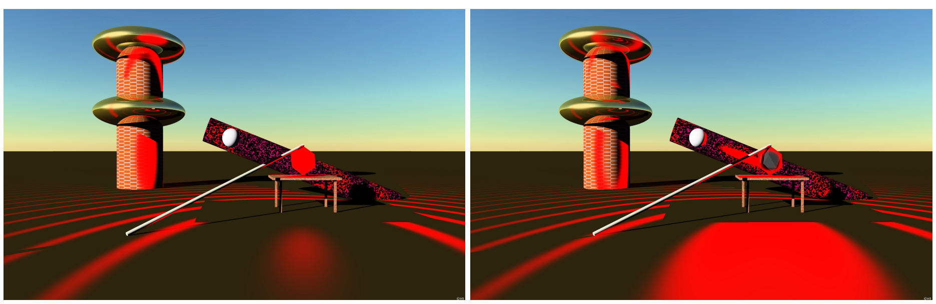

Fig. 1. Simulating a low, finite speed of light, we see the blinking light source casting multiple wavefronts propagating through the scene.

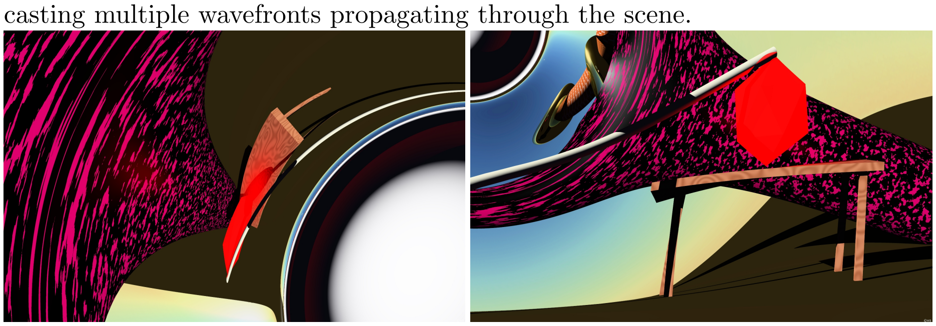

Fig. 2. The primary and secondary image of the light source on the desk; we see the desk from another perspective.

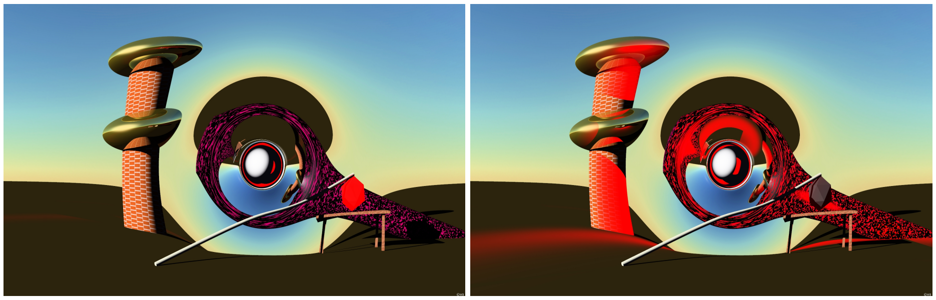

Fig. 3. Taking into account the finite speed of light, the blinking flash of the light source becomes first visible on the primary image. The secondary image does not flash until the primary image becomes dark again.

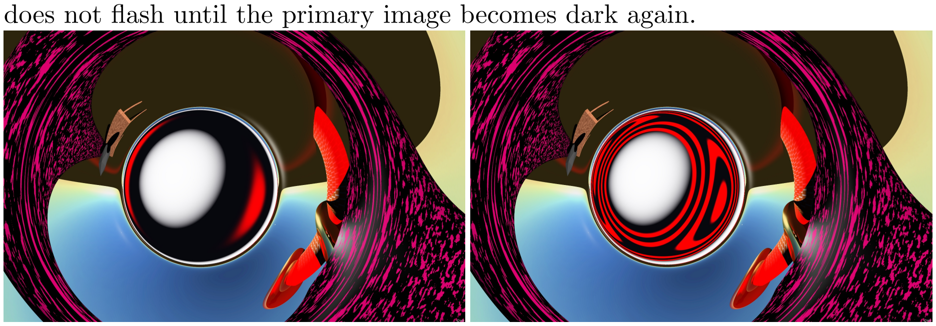

Fig. 4. Membrane radii of $r = 0.55, 0.505$ for an event horizon at $r = 0.5$. The time dilation allows us to see echoes of light pulses from far in the past.

References

1. Nemiroff, R.J.: Visual Distortions Near a Black Hole and Neutron Star. American Journal of Physics **61** (1993) 619+
2. Zahn, C.: Vierdimensionales Ray-Tracing in einer gekrümmten Raumzeit. Master's thesis, Inst. für Theoretische und Angewandte Physik Univ. Stuttgart (1991)
3. Weiskopf, D.: Visualization of Four-Dimensional Spacetimes. PhD thesis, Universität Tübingen (2001)
4. Benger, W.: Simulation of a black hole by raytracing. In F.W. Hehl, R.P., Ruder, H., eds.: Relativity and Scientific Computing - Computer Algebra, Numerics, Visualization, Berlin Heidelberg New York, Springer Verlag (1996) 2–3
5. Perlick, V.: Gravitational Lensing from a Spacetime Perspective. Living Rev. Relativity (7) (2004) `http://www.livingreviews.org/lrr-2004-9/`, cited 1.Dec.2005.
6. Shapiro, I.I.: Fourth Test of GR. Phys. Rev. Lett. (13) (1964) pp.789–791
7. Benger, W., Seidel, E.: Stereographic rendering of curved space. Presented at Supercomputing 2005, Seattle (2005)
8. Weiskopf, D., Kobras, D., Ruder, H.: Real-World Relativity: Image-Based Special Relativistic Visualization. In T.Ertl, B., A.Varshney, eds.: Visualization '00, ACM Press (2000) 303–310
9. Benger, W.: The light++ raytracing library. `http://www.photon.at/~werner/light/` (1990-2005)