Left: Alby and Limbradur set out on a journey through space and time. All images: Softmachine.

The characters enter the three-dimensional spacetime grid

The challenge:

Scientifically correct general theory of relativity in a fulldome environment

Christoph Brandl
3d Artist/Scientific Visualization
Softmachine
c.brandl@softmachine.de

A century of general relativity

The year 2015 marked the 100th anniversary of the release of Albert Einstein's general theory of relativity (GTR). Ten years after revolutionizing our comprehension of light in the special theory of relativity, Einstein did the same for the force of gravitation. While overturning our understanding of gravity, he also changed our view of the nature of space and time itself.

Probed to its most subtle predictions and confirmed countless of times, the GTR remains a theory of unsurpassed accuracy and elegance. It reinforced Einstein's status as a superstar of modern science and made him the epitome of a genius. Ironically, it is this standing as a prodigy that leads to reservations about engagement with the GTR in the greater public. People ask themselves, quite understandably, how could they could ever fathom a genius' masterpiece?

Two friends on a magical journey

To that end, Softmachine's new fulldome movie *The Secrets of Gravity: In the Footsteps of Albert Einstein* aims to introduce the GTR to a broad audience. It presents Einstein's findings to children and adults in a fun and playful way, and in doing so alleviates fears about abstract physics.

The 45-minute animated movie follows Limbradur, a student of the school of magic, who has become bored by all the sorcery. He'd rather be an astronaut when he's grown up. One night he breaks into the Albert Einstein museum, where he is caught by the resident knowledge-robot Alby X3. Limbradur is as intrigued by Alby's acquaintance with Albert Einstein as the robot is fascinated by the boy's magical powers. So they make a deal, where quirky Alby tells Limbradur all about gravity and the secrets of space and time.

The Munich-based animation studio Softmachine has over 10 years of experience in making fulldome movies and immersive content. Dr. Peter Popp (director, producer, writer) has produced the fulldome movies *Kaluoka'hina—The Enchanted Reef* (2004), *Realm of Light* (2008) and *The Life of Trees* (2013), before tackling gravitation. With the motto "emotional education," Softmachine has focused on combining compelling story lines with ambitious scientific content. In that vein, *The Secrets of Gravity* (2016) carefully interweaves the journey of two friends with the insights of the general theory of relativity.

The transition effect

For the fusion of character action with science documentary, we use a stylistic device, which we call the "transition effect." By simply waving his magic wand, Limbradur has the power to transform the set of the Albert Einstein museum into a form of "holodeck." With this virtual environment the characters can easily transport the audience anywhere and anytime, no matter if it is far away galaxies or abstract worlds of thought.

These science sequences are accompanied by the explanatory voiceover of know-it-all Alby, who is our guide through space and time. After a chapter about Isaac Newton and his discovery of gravity, the audience is introduced to the counter-intuitive phenomena of the GRT.

There are a number of challenges that come with the task of bringing scientifically correct, comprehensible—yet aesthetically pleasing—content to the screen or the dome. *Secrets* was rendered in stereoscopic 3D, which adds to the technical demands, but also adds to the explanatory power of many of the images.

Making Space three-dimensional

The characters enter a world that is far from reality. Through Limbradur's magic they see Einstein's thought experiments come to life. Step by step the museum, the earth, and even the stars and galaxies dissolve into nothing. This black emptiness is crisscrossed by blue glowing lines, extending in all directions. At last Limbradur and Alby find themselves standing in a semi-transparent lattice, where space is no longer just a notion of outer space, but one of dimension.

There is a well-established approach to the GRT, where the dimensions of space are represented as a form of fabric. Usually this is a simple two-dimensional plane. Instead, we show a three-dimensional grid, through which we create a bigger spatial and emotional impact. By placing the characters inside the 3D fabric, we invent a completely different immersive experience for the audience. This presentation comes with some caveats. If not for the characters, this world of blue lines leaves no point of reference for the eye to determine size.

To convey depth, one cannot simply add more lines in the background, as they start to overlay each other and the image becomes confusing. That's the reason why our lattice rapidly fades into the distance.

For full effect of this sequence, *Secrets* should be seen in stereoscopic 3D when possible. This is one of the cases where the sometimes maligned 3D is not simply a gimmick, but increases the perception of depth.

Bending space

For Einstein, space is not a rigid stage like in Newton's theory. It is flexible. Being in a bent space means that the shortest distance between two points is no longer a straight line, but a curve. So we demonstrate this fact by bending, waving, and deforming the lines of our grid.

But bending the lattice and seeing the bend are not the same thing when you produce images for the dome. In fact, the curved screen of the dome makes straight lines look warped anyway. So a lot of testing went into bending the lines far enough to be noticeable, but not too far as to affect the whole of the lattice.

As Einstein showed, space is deformed by the masses of objects inside of it. To demonstrate this fact, the Earth appears inside the grid. Its presence makes the lines move towards the planet's center of mass. This bend is what we feel as gravitation.

This three-dimensional representation of gravity avoids numerous pitfalls associated with the two-dimensional pendant (more on that later). Most of all, the center of gravity is easily and correctly identifiable as the Earth's core.

However, this presentation reaches its limits when we want the planet to move through the lattice. The lines in front of the Earth, in direction as if in flight, snap to its surface, whereas the lines on the rear side flick back to their initial straight shape. We tested this animation, but deemed all the overlapping lines too crowded for the viewer to discern what is happening. That's why our Earth does not drift into view, but magically materializes inside the lattice.

Likewise, problematic is a scenario with two planets inside the grid. Again, the progression of the lines gets increasingly chaotic and confusing. That's the reason why we have our thee-dimensional space collapse into a flat plane for the next shot.

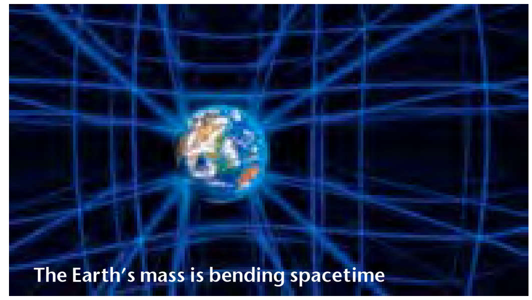
The Y-axis of our three-dimensional grid folds flat and leaves a smooth black plane with big blue lines intersected by smaller ones.

We did tests to match the size of the loops in the 3D and 2D grids and found out that grid loops that are too small for the three-dimensional are still too big for the two dimensions. So in the 3D lattice we use larger loops, whereas in the grid we subdivide those bigger loops with smaller ones.

We also noticed, when the loops are too small or the camera is too far above it respectively, a distracting moire effect sets in at the far edges of the grid. Then again, the problem with straight lines in the dome is much less pronounced on the flat surface. It only becomes apparent when you tilt the camera too far down, that the plane no longer looks flat but convex.

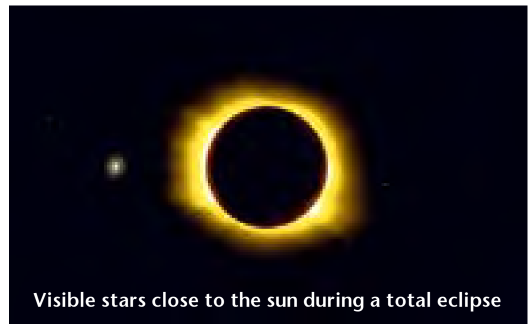
Below our two-dimensional grid, we see a massive bulge forming. As the camera switches to the other side of the fabric, we realize it is again the planet Earth that's causing the depression. In this hollow the smaller moon circles around our planet, like a marble rolls inside a funnel.

Here gravity is represented by the dent, pressed by the planet's mass into the fabric of space. Showing space as three-dimensional may be closer to the real world, but as already indicated, there are cases where the reduction to only two dimensions adds clarity and comprehensibility. We can, for example, show two objects in movement and interaction with each other. In this case, the moon's gravity is only a smaller dent inside the big funnel around the Earth. This fabric analogy is the common visualization of space in the GRT.



The Earth's mass is bending spacetime

The moon is circling inside Earth's gravity well



Visible stars close to the sun during a total eclipse

Light from a distant star is bent by the sun's gravity

Light going in curves

The general theory of relativity's first testable consequence was the deflection of light by gravity. Einstein predicted that any sufficient mass, like a star or planet, would bend a beam of light passing close to it. From the perspective of the light, it is moving in a straight line through space; it is space itself that has a bent shape.

In *Secrets* we discuss Sir Arthur Eddington's famous experiment from May 29, 1919.

(Continues on next page)

The acclaimed astronomer used a total solar eclipse to verify a consequence of the GTR for the very first time. According to Einstein, the sun's huge mass bends its surrounding space, so that passing light will be deflected. Now usually you can't see the sun and the stars at the same time, as our central orb outshines them. Only during a total eclipse, when the moon completely covers the face of the sun, there is a moment where it is possible to photograph the background stars.

When this picture is then compared to an image of the night sky, the apparent position of the stars close to the sun will have shifted. Eddington was able to show this with a cluster of stars. Close to the sun, the image of the stars had moved to a virtual position, not corresponding to their real location in the sky.

Einstein had been proven correct. As the GTR mastered its first encounter with experiment, it changed from a pure hypothesis to a respected theory with true predictive power for the real world.

Our scenario starts with the robot Alby looking through the telescope of the Einstein museum. Cut to Alby's point of view. We see what Arthur Eddington observed back then: The moon plodding in front of the sun, until it is dark enough to see the stars. In that moment the viewer leaves the telescope aperture and the look of the scene quickly changes into our space grid. This is how we create a visual bridge from our characters, via the experiment, to it's schematic explanation.

We are again looking over our grid, with Earth, the moon and the sun aligned in a row. One highlighted star from beyond the grid emanates a ray of light. The beam approaches us in slow-motion, is deflected by the sun's gravity well, passes the moon and finally hits the surface of the Earth.

Eddington's experimental set-up is sometimes beholden to misconceptions. Speaking from experience, it is the role of the moon that is quite often misunderstood. It is erroneously thought as the originator of the light's curvature, instead of its actual role as natural cover for the sun's glare. In our animation this becomes obvious, as the beam of light is not visibly affected by the moon. Although any mass bends space—and the moon has a significant gravitational field itself—the moon's influence on the ray is still negligible when compared to the sun's.

When you see drawings of this experiment, the artist usually shows the virtual position of the star together with its actual location. Here we avoid this doubling, by slowly moving our hero-star from its location seen in the telescope, to its true place in the grid-view.

What you measure with a clock

One of the most heard of and least understood consequences of the GRT is the relativity of time. Einstein realized that the dimensions of space and time are not separate, but are woven together in what he called spacetime. And just like masses bend space, they also affect time. But what is time? For witty Albert Einstein, it is simply "what you measure with a clock."

Left: Every point in space has its own passage of time

Below: Space and time are woven together in spacetime

Two observers in different fields of gravity will each experience time in exactly the same way. One second will be one second to their clocks, not more or less. But when the two of them meet again after a while and compare their watches, they will see that they don't display the same time. Every observer has his own unique time, depending where he is in space. For someone in a higher field of gravity, time passes slower. That means that on Earth, time passes a few picoseconds slower than on the moon. Using atomic clocks, scientists even measured the minuscule time difference between being on a mountain top, and being in the valley.

In the movie we symbolize time's relativity with a multiplicity of loud ticking clocks. They sit virtually at every spot, to illustrate that any point in space is equipped with its own time.

To experience the dilation of time, we slow down the ticking-sound correspondingly to the increasing gravitation as the camera descends ever closer to Earth.

By placing our clocks at the nodes of our three-dimensional lattice, we extend our visualization of space to also encompass time: enter Albert Einstein's spacetime.

Beautiful, but useful

An important message of the movie is to point out the practical use of the general theory of relativity. At time of release, Einstein's relativity was considered "beautiful," but there was no technical application in sight.

Some 100 years later, this has changed. One prime example is the global positioning system, a constellation of satellites that tell navigation systems where they are exactly. GPS depends on the precise measurement of time. Every one of the 24 active satellites simply broadcasts its own time. By measuring the time differences between the signals of the satellites, the navigational system can determine its own location on Earth.

This means, simply, that the accuracy of GPS depends on the precise measurement of time. But without considering general relativity, the satellites' internal clocks would deviate so much after just one day as to be off by a few miles. Without the GTR, navigational devices would not work.

Our camera pan starts between the Earth and the orbits of the GPS satellites. The viewer is surrounded by the indicated orbital paths, using the dome projection to full capacity. The camera slowly backs away and we see how the planet is encircled by the satellites, giving it the aesthetics of Niels Bohr's atomic model.

What color is a black hole?

The most exotic consequence of Einstein's general theory of relativity is the infamous black hole. When a giant star simultaneously explodes and implodes at the end of its life, its enormous mass gets compressed in a tiny point of space. A black hole is born. A black

(Continues on page 54)

hole is a place in spacetime where the density of matter is so high, and the resulting gravity so strong, that not even light can escape. The point-of-no-return is called the event horizon. Everything that disappears behind this horizon is lost forever.

No one knows what the inside of a black hole looks like, and if the established laws of physics—including the GTR itself—still apply under these extreme circumstances. This is where some of the biggest secrets of space and time are hidden. It is up to the next "Einstein" to solve this riddle.

In *Secrets,* the audience encounters a black hole as our two-dimensional spacetime grid starts to form a funnel that extends to infinity. The camera approaches the funnel's upper side and we see the black hole lying inside the vast gravity well.

Before even knowing what is inside a black hole, telescopes have yet to get sensitive enough to see one up close. But how could you see something that emits no light? And how do you present it in a movie?

A black hole may be invisible, but it reveals itself by its effects on the surroundings. Far from the "vacuum cleaners" science fiction makes them out to be, black holes can still have an immense impact on their environment. Stars and gas clouds getting too close to the event horizon can plunge inside. When they do, they don't fall in a straight line, but circle down the gravity well in a kind of death spiral.

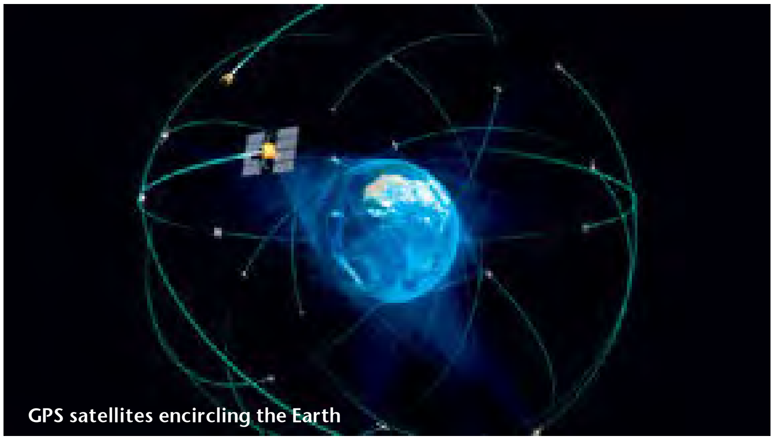
This disc of super-heated matter is bright enough to get picked up by telescopes. Paradoxically, this process makes some black holes the brightest objects in the whole universe! So in *Secrets* we show exactly this death spiral, but toned down in brightness for reasons of clarity.

As we get closer to the event horizon, the lines of the spacetime grid fade out to show how the background stars are warped by the black hole's gravity.

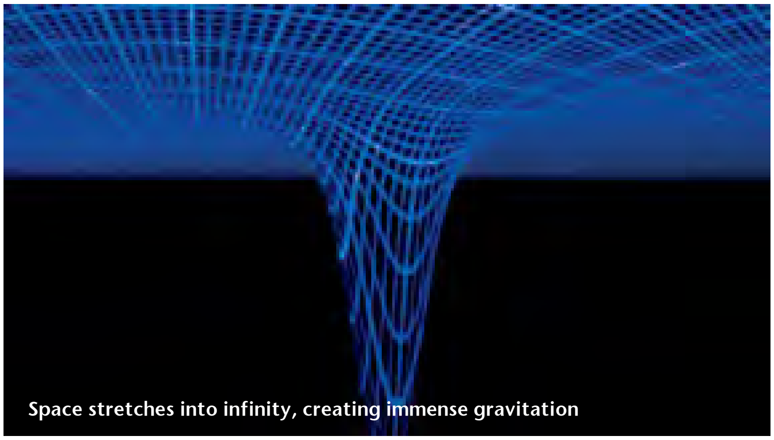
The biggest challenge in visualizing the black hole lies in its enormous bending of light. The immense gravitation causes an outlandish optical illusion, where the image of the surrounding gas is doubled above and below the black hole. As there are no gravity-emitters in our render engine that affect its ray-tracing, we had to create this effect by optical means only.

The gravitational lens is simulated by an array of optical lenses. Just as one can approximate a circle shape by finely subdividing a polygon, a ray of light can look bent by refracting it ever more.

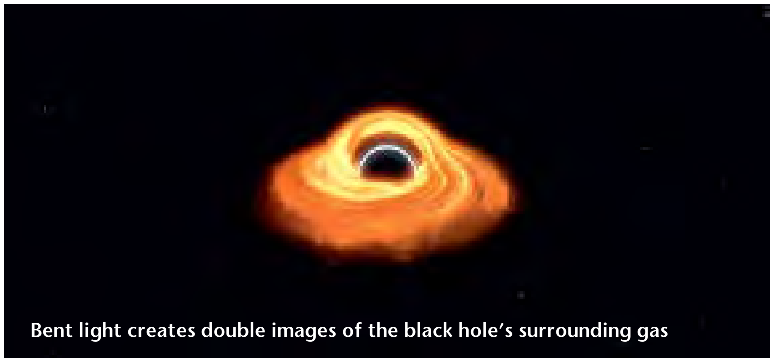
To underscore the black hole's infinite gravity well, we use stereoscopic 3D to create extraordinary depth inside. This is a visual effect that fascinates and tantalizes at same time, and cannot be seen in the 2D version of the movie.



GPS satellites encircling the Earth



Space stretches into infinity, creating immense gravitation



Bent light creates double images of the black hole's surrounding gas

The sound of gravity

The year of Albert Einstein, 2015, was topped off by the first direct measurement of gravitational waves this past year. The Laser Interferometer Gravitational-Wave Observatory (LIGO) saw how spacetime was stretched and compressed a tiny bit. The signal corresponded to the merging of two black holes, a long time ago in a far away galaxy. That gravitation propagates as waves was the GTR's biggest unproven prediction. And again, Einstein was proven right.

You can hardly underestimate the importance of this breakthrough for astronomy. It opens up a completely new way to experience the universe. Up to that date, we were limited to seeing the cosmos; now we can also hear it. This allows the exploration of invisible phenomena, like black holes, dark matter, and the big bang.

And, as always, we will find things we don't even expect yet. As Albert Einstein once said: "It is entirely possible that behind the perception of our senses, worlds are hidden of which we are unaware."

The announcement of gravitational waves coincided with the release of *Secrets.* With this discovery, we can expect that even 100 years after its release, the importance of Einstein's theory will still increase. This makes it a timely concern to introduce the basics and consequences of the general theory of relativity to everyone. To that end, *Secrets* hopes to make the coming generation aware of the accomplishments of science and the beauty of the universe. ☆