
Close-Up Black Hole
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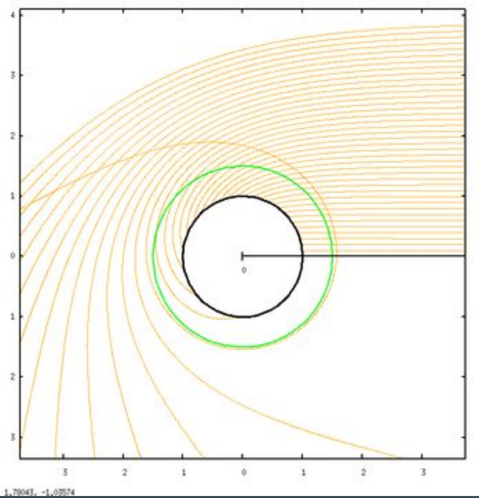
Hemisphere Sampling
256 samples/pixel
64 shadow rays
5 max ray depth
1920x1080

Quantitative Ray Tracing in General Relativity

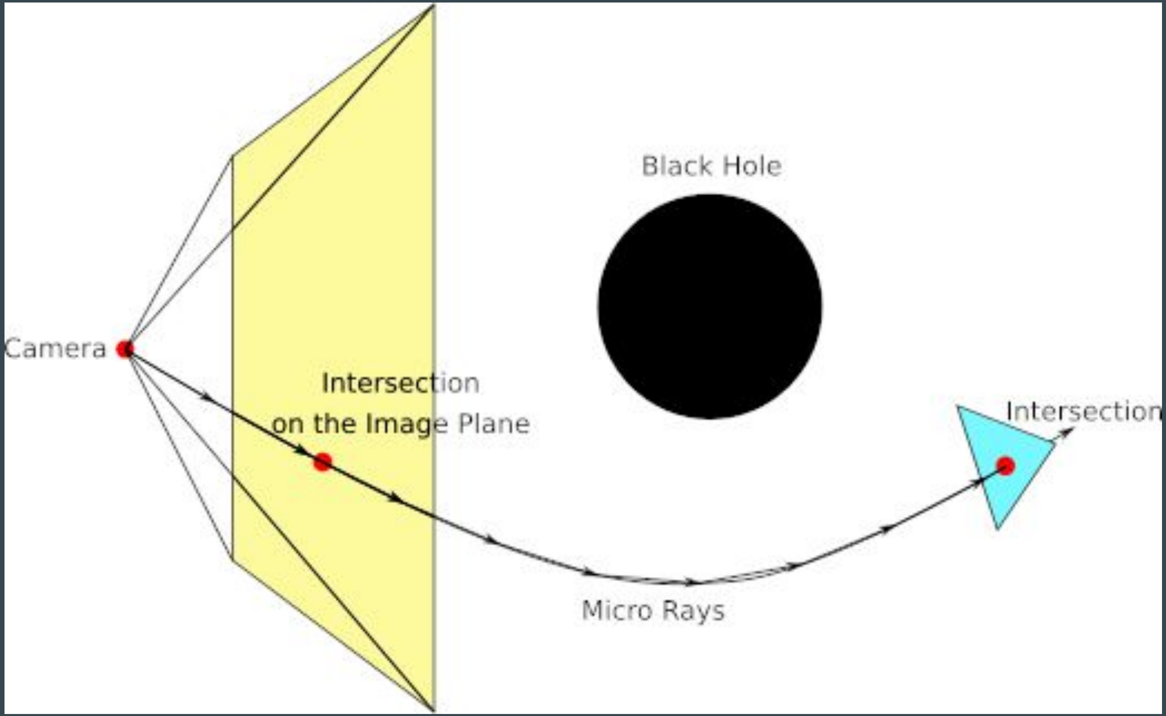
- Light bends near massive objects
- Curves that light travel on are determined by non-linear ODE
- Solution : Numerical integration



Graph of light geodesics for a Schwarzchild black hole

(Source : http://spiro.fisica.unipd.it/~antonell/schwarzschild/)

Integrating the Geodesic Equation : Schwarzchild Black Hole

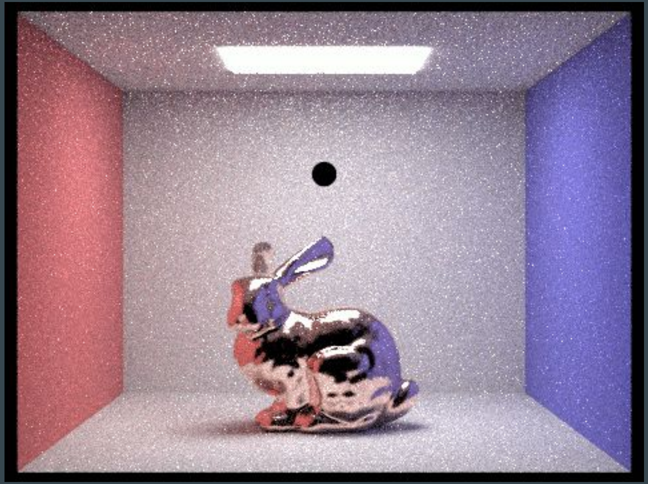


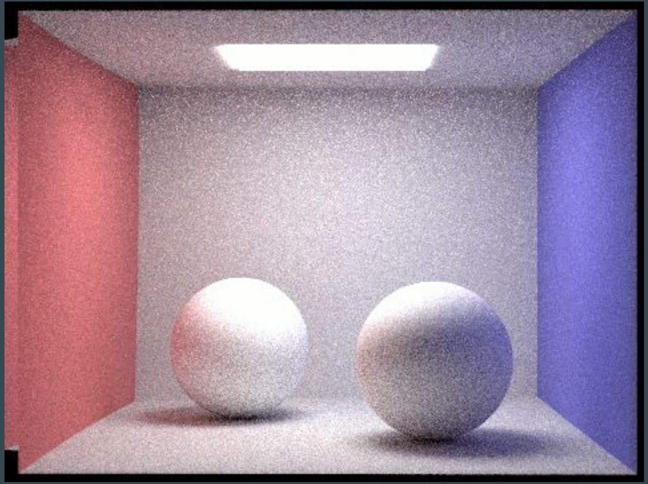
Integrating the Geodesic Equation : Schwarzchild Black Hole

- Strategy: adapt project 3 to cast rays as geodesics instead of lines
  - Cast a ray into the scene
  - Determine the next point on the geodesic using numerical integration
  - Use the ray defined as connecting the original point to the next point & intersect with scene
  - If not continue ad infinitum (or user defined bound)
- Ray curve determined by a non-linear differential equation
  - $u'' + u = 3r_s u^2/2$, where $u(\theta) = 1/r(\theta)$
  - Initial conditions given by ray origin and direction
- Use 4^{th} order Runge Kutta numerical integration for improved numerical stability at same step size
  - Steps can be much larger speeding up rendering

Black Hole Warping

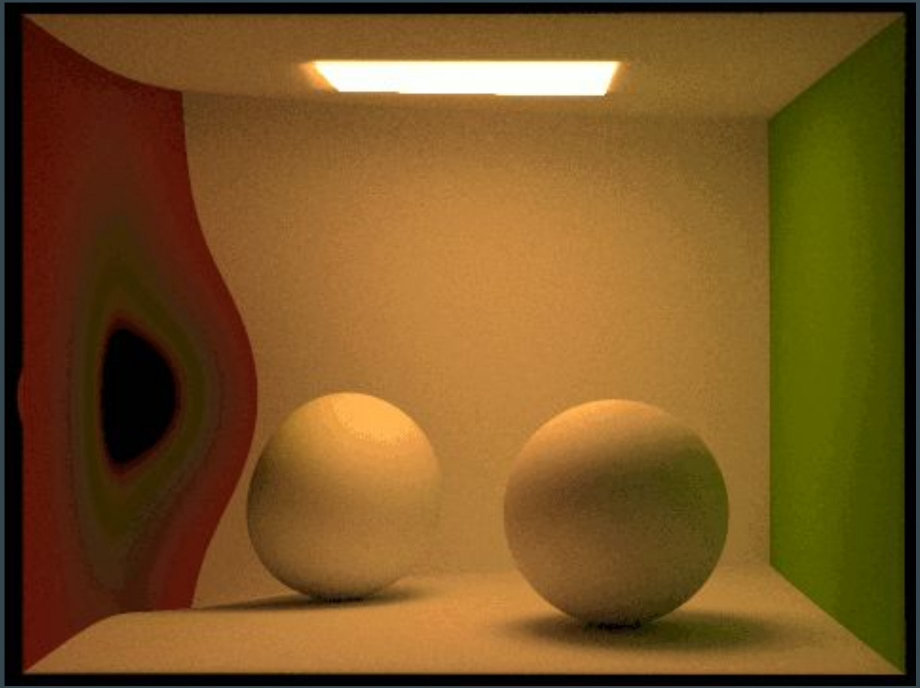
- Key features
  - Spherical distortion
  - Gravitational lensing
    - Notice that the black hole focuses the light onto the wall
  - Ghost image
    - I.e. the colored wall appears inverted





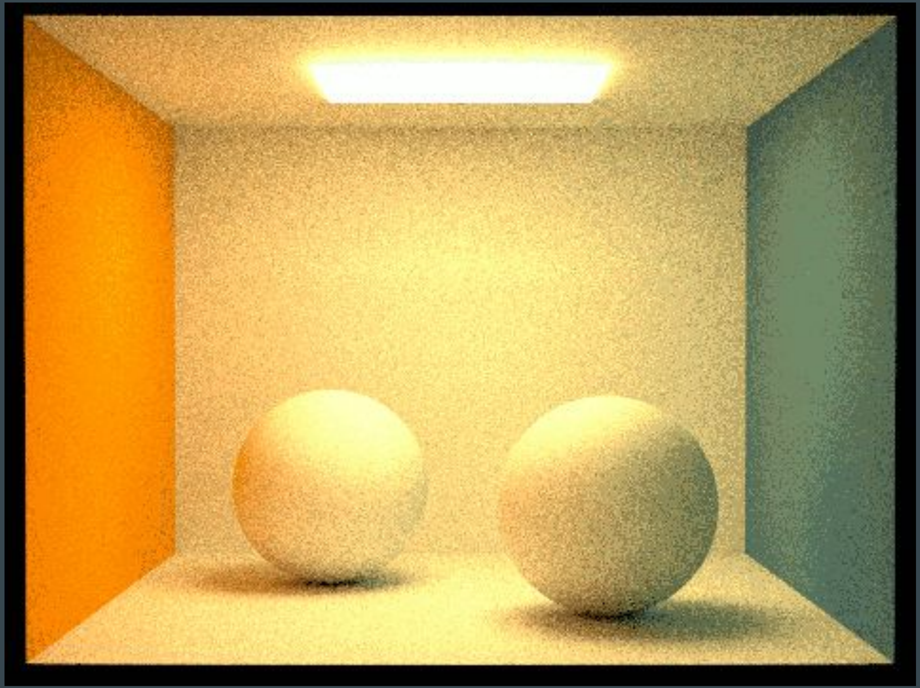
Light Spectrum

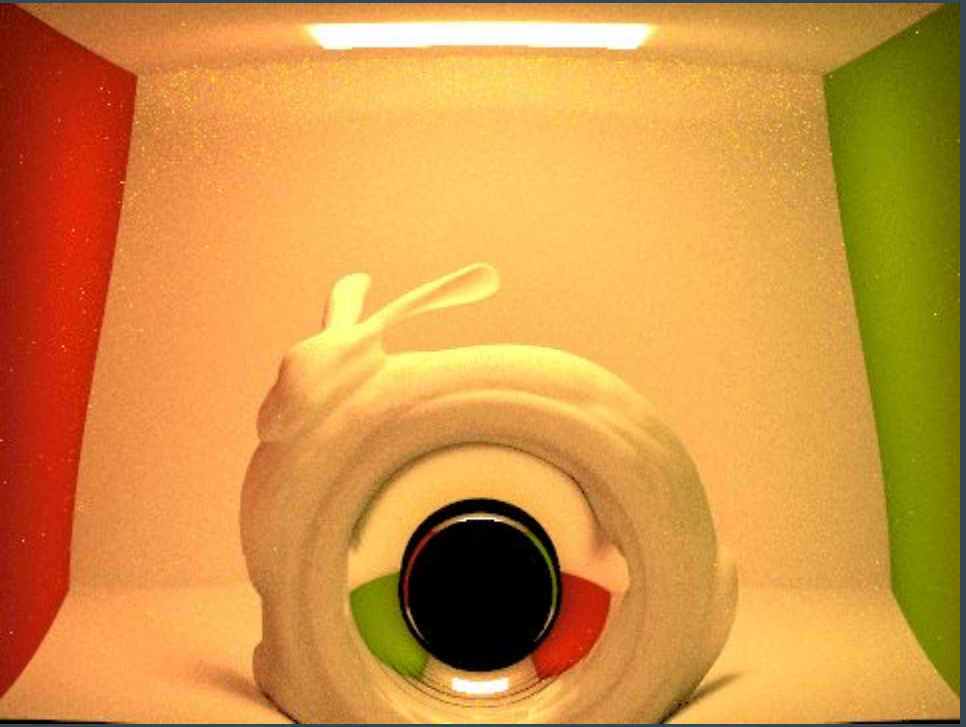
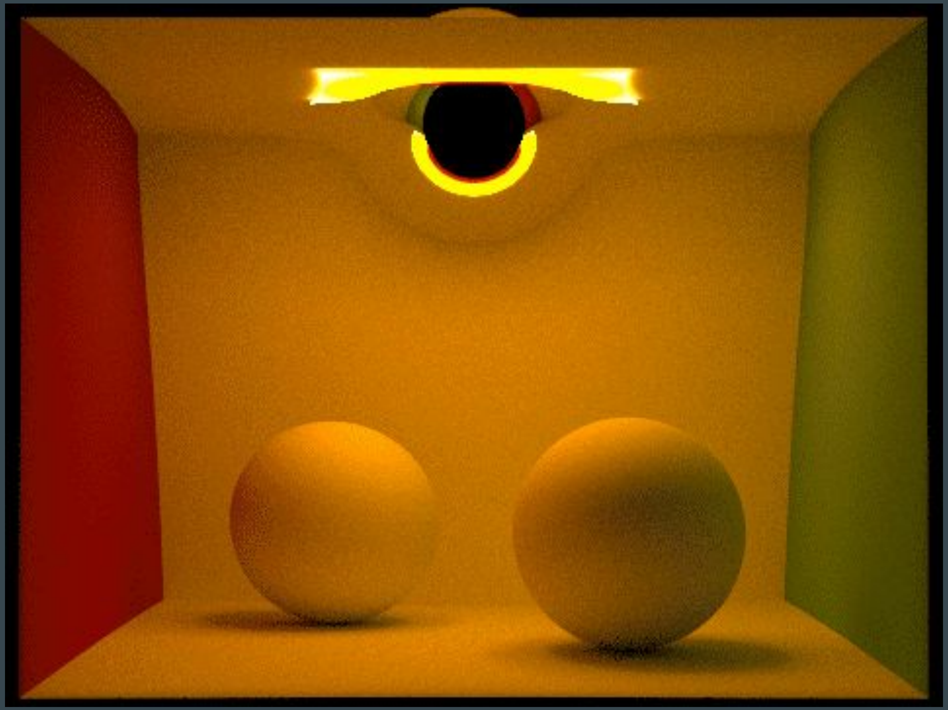
- Used spectral data from cornell box
  - 76 wavelength channels for intensity
  - 400nm - 700nm visible range
  - 4nm resolution
- Used analytic approximation for 1931 CIE XYZ observer
- Converted XYZ to sRGB with M^{-1}



Gravitational Doppler Effect

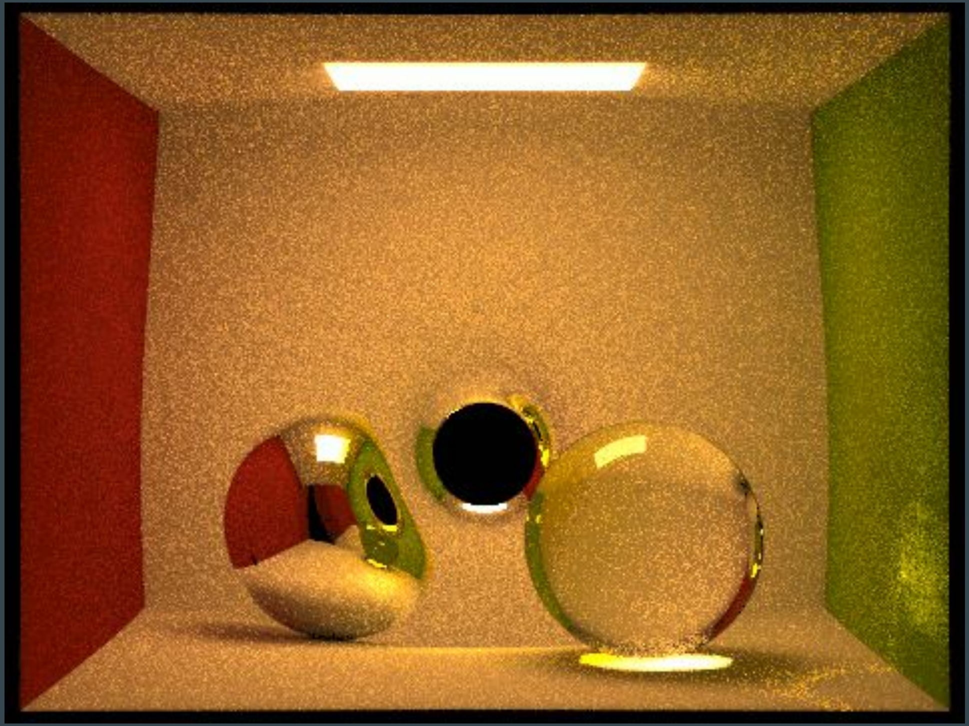
- So far ignored wave nature of light
- Spacetime changes the speed of light, thus changing wavelength of light ray
- Light red shifts away from gravitational source, blue shifts towards
- Notice light spectrum redshifts towards the camera



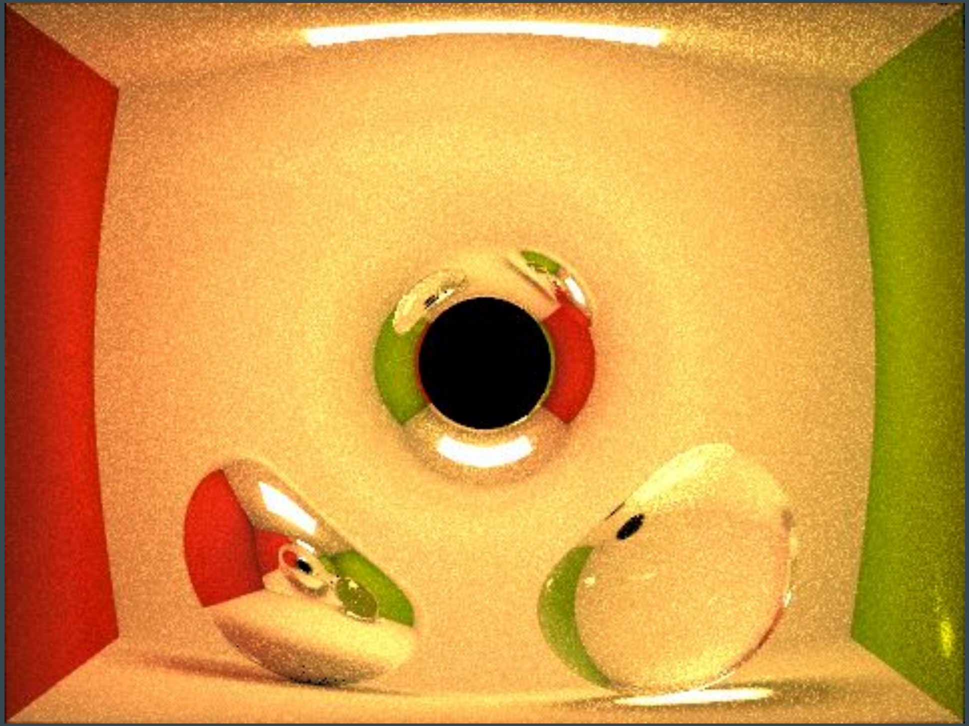



Light Scattering

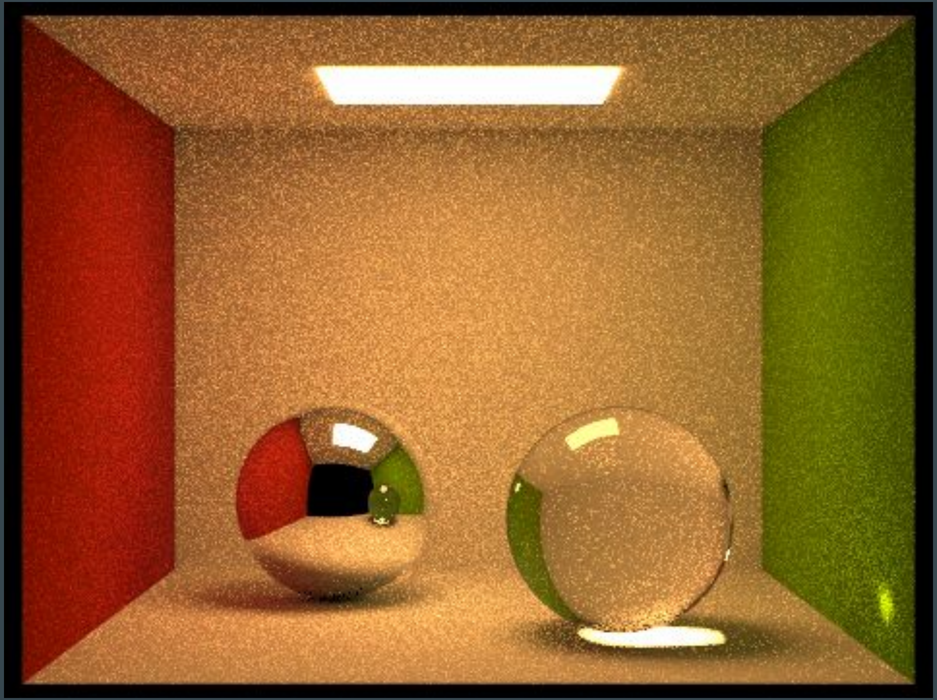
- Defocusing on glass sphere
- Note red in mirror
  - -Usually all black

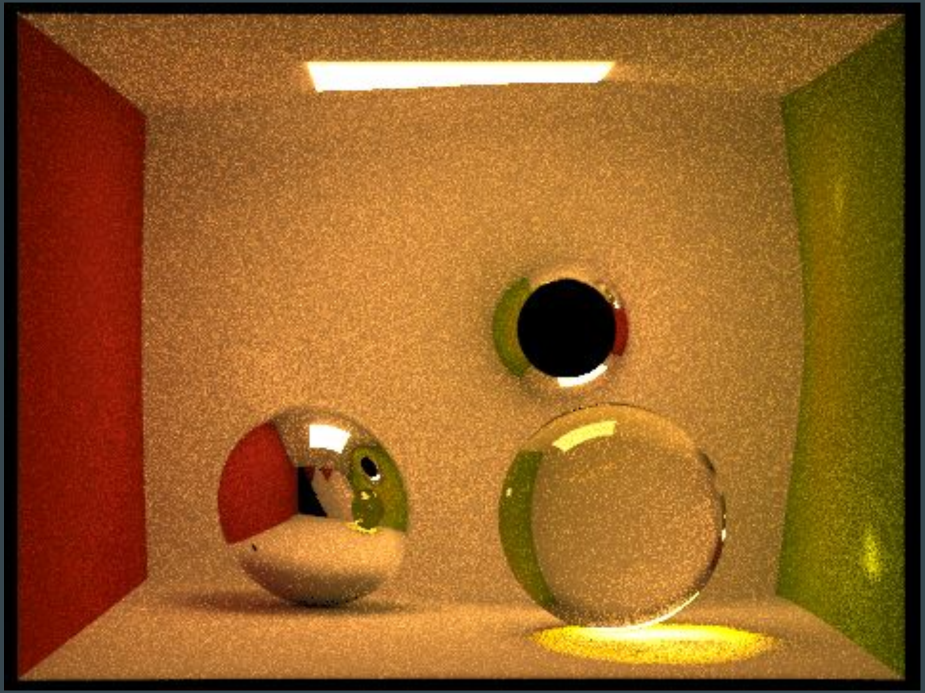


MirrorBSDF: Nested Mirror-Blackhole Ghost Image



MirrorBSDF: secondary bright spots





Why This Topic is Interesting

- This project tackles three big topics in the course:
  - Numerical Integration
  - Ray Tracing
  - Color

What Did We Learn?

- Forward Euler vs. 4th Order Runge Kutta
    - 4th Order Runge Kutta gives better results
- Color with just RGB is difficult
    - Red shifts out, green stays in spectrum, blue turns green.

Next Steps (hopefully)

- Implement a Kerr black hole with spin (different differential equation) and corresponding Doppler shift
    - Very hard, 5 equations must be solved simultaneously
    - Spherical symmetry is broken
- Implement numerical metric to support construction of arbitrary black hole configuration