

General Relativity exercises

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We set $c = 1$.

Here we will often use (anti)symmetrization of indices, which makes some calculations much easier. The idea of symmetrization is to sum over all permutation of the selected indices, with a minus sign for the odd permutation if the case of anti symmetrization. So, for instance, $F_{\mu\nu}$ can be antisymmetrized into $F_{[\mu\nu]} = 1/2(F_{\mu\nu} - F_{\nu\mu})$ and symmetrized into $F_{(\mu\nu)} = 1/2(F_{\mu\nu} + F_{\nu\mu})$.

The factor $1/2$ is in general $1/n!$, where n is the number of antisymmetrized indices. This is included because in general we will be summing $n!$ terms, and we want to write things like: “ $F_{\mu\nu}$ is antisymmetric means $F_{\mu\nu} = F_{[\mu\nu]}$ ”, so we need to rescale the sum to make it into an average.

The general formulas are then:

$$F_{[\mu_1 \dots \mu_n]} = \frac{1}{n!} \sum_{\sigma \in \mathfrak{S}_n} \text{sign}(\sigma) F_{\sigma(\mu_1) \dots \sigma(\mu_n)} \quad (0.1a)$$

$$F_{(\mu_1 \dots \mu_n)} = \frac{1}{n!} \sum_{\sigma \in \mathfrak{S}_n} F_{\sigma(\mu_1) \dots \sigma(\mu_n)} , \quad (0.1b)$$

where \mathfrak{S}_n is the *symmetric group* of permutations of n elements, and the sign of a permutation $\sigma \in \mathfrak{S}_n$ is ± 1 , depending on the parity of pair swaps that are needed to get that configuration (we fix $\text{sign}(\mathbb{1}) = 1$).

If we want to symmetrize indices which are not next to each other, we will denote the end of the (anti)symmetrized indices by a vertical bar.

Sheet 1

1.1 Lorentz transformations

1.1.1 Inverses

We can consider a Lorentz boost with velocity v in the x direction, and we look at its representation in the (t, x) plane (since the y and z directions are unchanged). Its matrix expression looks like:

$$\Lambda = \begin{bmatrix} \gamma & -v\gamma \\ -v\gamma & \gamma \end{bmatrix}, \quad (1.1)$$

where $\gamma = 1/\sqrt{1-v^2}$. The inverse of this matrix can be computed using the general formula for a 2x2 matrix:

$$A^{-1} = \begin{bmatrix} a & b \\ c & d \end{bmatrix}^{-1} = \frac{1}{\det(A)} \begin{bmatrix} d & -b \\ -c & a \end{bmatrix}. \quad (1.2)$$

The determinant of Λ is equal to $\gamma^2(1-v^2) = 1$, therefore the inverse matrix is:

$$\Lambda = \begin{bmatrix} \gamma & v\gamma \\ v\gamma & \gamma \end{bmatrix}. \quad (1.3)$$

1.1.2 Invariance of the spacetime interval

Our Lorentz transformation is

$$dt' = \gamma(dt - v dx) \quad (1.4a)$$

$$dx' = \gamma(-v dt + dx) \quad (1.4b)$$

$$dy' = dy \quad (1.4c)$$

$$dz' = dz \quad (1.4d)$$

and we wish to prove that the spacetime interval, defined by $ds^2 = \eta_{\mu\nu} dx^\mu dx^\nu$ is preserved: $ds'^2 = ds^2$. Let us write the claimed equality explicitly:

$$-dt^2 + dx^2 + dy^2 + dz^2 = \gamma^2(dt - v dx)^2 + \gamma^2(-v dt + dx)^2 + dy^2 + dz^2 \quad (1.5a)$$

1.1.3 Tensor notation pseudo-orthogonality

The invariance of the spacetime interval $ds'^2 = ds^2$ can be also written as $\eta_{\mu\nu} dx^\mu dx^\nu = \eta_{\mu\nu} dx'^\mu dx'^\nu$. By making the primed differentials explicit we have:

$$\eta_{\mu\nu} dx^\mu dx^\nu = \eta_{\mu\nu} \Lambda^\mu_\rho dx^\rho \Lambda^\nu_\sigma dx^\sigma, \quad (1.6)$$

but the dummy indices on the LHS can be changed to ρ and σ , so that both sides are proportional to $dx^\rho dx^\sigma$. Doing this we get:

$$\eta_{\rho\sigma} = \eta_{\mu\nu} \Lambda^\mu_\rho \Lambda^\nu_\sigma = (\Lambda^\top)_\rho^\mu \eta_{\mu\nu} \Lambda^\nu_\sigma, \quad (1.7)$$

or, in matrix form, $\eta = \Lambda^\top \eta \Lambda$.

1.1.4 Explicit pseudo-orthogonality

For simplicity but WLOG we consider a boost in the x direction with velocity v and Lorentz factor γ . The matrix expression to verify is:

$$\begin{bmatrix} \gamma & -v\gamma \\ -v\gamma & \gamma \end{bmatrix} \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \gamma & -v\gamma \\ -v\gamma & \gamma \end{bmatrix} \stackrel{?}{=} \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix} \quad (1.8a)$$

$$\begin{bmatrix} \gamma & -v\gamma \\ -v\gamma & \gamma \end{bmatrix} \begin{bmatrix} -\gamma & v\gamma \\ -v\gamma & \gamma \end{bmatrix} \stackrel{?}{=} \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix} \quad (1.8b)$$

$$\begin{bmatrix} -\gamma^2 + \gamma^2 v^2 & v\gamma^2 - v\gamma^2 \\ v\gamma^2 - v\gamma^2 & -v\gamma^2 + \gamma^2 \end{bmatrix} = \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix}, \quad (1.8c)$$

which by $\gamma^2 = 1/(1 - v^2)$ confirms the validity of the expression.

1.2 Muons

1.2.1 Nonrelativistic approximation

The survival probability is given by $\mathbb{P}(t) = \exp(-t/2.2 \times 10^{-6} \text{ s})$. If the ground is $h = 15 \text{ km}$ away, then the muon will reach it in $t = h/v = 15 \text{ km}/(0.995c) \approx 5.03 \times 10^{-5} \text{ s}$, therefore $\mathbb{P}(t) \approx 1.2 \times 10^{-10}$.

1.2.2 Relativistic effects: ground perspective

The observer on the ground will see the muon having to traverse the whole $h = 15 \text{ km}$, but the muon's time will be dilated for them by a factor $\gamma_v \approx 10$: therefore the survival probability will be $\mathbb{P}(t) = \exp(-t/(\gamma_v \times 2.2 \times 10^{-6} \text{ s})) \approx 0.1$.

1.2.3 Relativistic effects: muons perspective

The muons in their system will observe length contraction, with respect to Lorentz boost, by a factor $\gamma_v \approx 10$: therefore the survival probability will be $\mathbb{P}(t) = \exp\left(-t/(\gamma_v \times 2.2 \times 10^{-6} \text{ s})\right) \approx 0.1$. This result is the same of the one predicted by ground observer, with respect to relativity principle.

1.3 Radiation

1.3.1 New angle

In the source frame the radiation velocity components are $u'_x = \cos \theta'$, $u'_y = \sin \theta'$. From the composition of velocities we obtain:

$$u_y = \sin \theta = \frac{dy}{dt} = \frac{dy'}{\gamma_v(dt' + v dx')} = \frac{\sin \theta'}{\gamma_v(1 + v \cos \theta')} \quad (1.9a)$$

$$u_x = \cos \theta = \frac{dx}{dt} = \frac{\gamma_v(dx' + v dt')}{\gamma_v(dt' + v dx')} = \frac{\cos \theta' + v}{1 + v \cos \theta'} \quad (1.9b)$$

hence:

$$\frac{1}{\tan \theta} = \frac{\gamma_v}{\tan \theta'} + \frac{\gamma_v v}{\sin \theta'}. \quad (1.10)$$

1.3.2 Angle plot and relevant limits

See the jupyter notebook in the python folder for plots. For $v = 0$ we have $\theta = \theta'$ as we expected, while for $v = 1$, $\theta = 0$.

1.3.3 Radiation speed invariance

Are the components of the velocity, which we called $\sin \theta$ and $\cos \theta$, actually normalized? Let us check:

$$\sin^2 \theta + \cos^2 \theta = \frac{\left(\frac{\sin \theta'}{\gamma_v}\right)^2 + (\cos \theta' + v)^2}{(1 + v \cos \theta')^2} \quad (1.11a)$$

$$= \frac{(1 - v^2) \sin^2 \theta' + \cos^2 \theta' + v^2 + 2v \cos \theta'}{(1 + v \cos \theta')^2} \quad (1.11b)$$

$$= \frac{1 + v^2(1 - \sin^2 \theta') + 2v \cos \theta'}{(1 + v \cos \theta')^2} = 1, \quad (1.11c)$$

therefore the square modulus of the speed of the radiation is still c , as we could have assumed earlier.

1.3.4 Isotropic emission

Since the angular distribution of emission varies when changing inertial reference, we might suppose that every system in relative motion respect to O with $v \neq 0$ observes nonisotropic emission.

This can be seen by noticing that for $v \simeq 1$ we have that in the observer system there is almost only emission at an angle $\theta = 0$. In general, since there is a Lorentz γ factor multiplying a function of the angle in the radiation emission frame O' , the cotangent of the angle in the observation frame O must get larger and larger as the relative velocity v increases, therefore the radiation gets compressed towards angles with large cotangents: $\theta \sim 0$.

See the jupyter notebook in the python folder for interactive plots :)

Sheet 2

2.1 Constant acceleration

2.1.1 Coordinate velocity

We are given the position as a function of time,

$$x(t) = \frac{\sqrt{1 + \kappa^2 t^2} - 1}{\kappa}, \quad (2.1)$$

and we can directly compute its derivative

$$v(t) = \frac{dx}{dt} = \frac{\kappa t}{\sqrt{\kappa^2 t^2 + 1}} = \frac{1}{\sqrt{\frac{1}{\kappa^2 t^2} + 1}}. \quad (2.2)$$

It is clear from the expression that $|v| < 1$ for all times, while v approaches 1 at positive temporal infinity and -1 at negative temporal infinity.

2.1.2 Components of the 4-velocity

The Lorentz factor γ is given by

$$\gamma = \frac{1}{\sqrt{1 - v^2}} = \frac{1}{\sqrt{1 - \frac{\kappa^2 t^2}{\kappa^2 t^2 + 1}}} = \sqrt{\kappa^2 t^2 + 1}, \quad (2.3)$$

therefore the four-velocity is given by:

$$u^\mu = \begin{bmatrix} \gamma \\ \gamma v \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} \sqrt{\kappa^2 t^2 + 1} \\ \kappa t \\ 0 \\ 0 \end{bmatrix}. \quad (2.4)$$



Figure 1: Velocity as a function of coordinate time t

2.1.3 Proper time

The relation between coordinate and proper time is given by the definition of the first component of the four-velocity: $u^0 = dt/d\tau = \gamma$, therefore $d\tau = dt/\gamma$. Integrating this relation we get:

$$\tau = \int_0^\tau d\tau' = \int_0^t \frac{dt'}{\gamma(t')} = \frac{\text{arcsinh}(\kappa t)}{\kappa}, \quad (2.5)$$

where the constant of integration is selected by imposing $t = 0 \iff \tau = 0$. Notice that, as we would expect, when expanding up to first order near $t = \tau = 0$ we have $t \sim \tau$, since in that region the velocity is much less than unity.

The inverse relation is given by $t = \sinh(\kappa\tau)/\kappa$. Using this, we can write:

$$x(t(\tau)) = \frac{\cosh(\kappa\tau) - 1}{\kappa}. \quad (2.6)$$

2.1.4 Four-acceleration

Now, we wish to compute the four-acceleration. There are many ways to approach this: an easy one is to simply find the explicit expression $u^\mu(\tau)$ and to differentiate

it. The expression we get is:

$$a^\mu = \frac{d}{d\tau} u^\mu = \frac{d}{d\tau} \begin{bmatrix} \frac{\sqrt{\sinh^2(\kappa\tau) + 1}}{\sqrt{\kappa^2 t^2 + 1} \sinh(\kappa\tau)} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} \frac{\sqrt{2\kappa} \sinh(2\kappa\tau)}{2\sqrt{\cosh(2\kappa\tau) + 1}} \\ \kappa \cosh(\kappa\tau) \\ 0 \end{bmatrix}, \quad (2.7)$$

which is a bit unwieldy but it can be used to check two important facts: $a^\mu a_\mu = \text{const}$ and $a^\mu u_\mu = 0$. The first of the two is:

$$a^\mu a_\mu = -(a_0)^2 + (a_1)^2 = \kappa^2 \cosh^2(\kappa\tau) - \frac{\kappa^2 \sinh^2(2\kappa\tau)}{2(\cosh(2\kappa\tau) + 1)} = \kappa^2, \quad (2.8)$$

which tells us that the constant acceleration $\sqrt{a^\mu a_\mu} = \kappa$.

Also, we verify the orthogonality to the four-velocity:

$$a^\mu u_\mu = -\frac{\sqrt{2\kappa} \sqrt{\sinh^2(\kappa\tau) + 1} \sinh(2\kappa\tau)}{2\sqrt{\cosh(2\kappa\tau) + 1}} + \kappa \sinh(\kappa\tau) \cosh(\kappa\tau) = 0. \quad (2.9)$$

2.1.5 Local velocity & acceleration

We can apply a Lorentz boost corresponding to this velocity: it will be given by the matrix:

$$\begin{bmatrix} \gamma & -v\gamma & 0 & 0 \\ -v\gamma & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (2.10)$$

where v and γ are those found before. Without doing any calculations we could already say that the transformed velocity will be equal to the time-like unit vector, while the acceleration will be equal to κ times the unit x -directed vector.

The velocity becomes:

$$(u^\mu)' = \begin{bmatrix} \sqrt{\kappa^2 t^2 + 1} & -\kappa t & 0 & 0 \\ -\kappa t & \sqrt{\kappa^2 t^2 + 1} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \sqrt{\kappa^2 t^2 + 1} \\ \kappa t \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \quad (2.11)$$

as we expected.

The acceleration instead becomes:

$$(a^\mu)' = \begin{bmatrix} \sqrt{\kappa^2 t^2 + 1} & -\kappa t & 0 & 0 \\ -\kappa t & \sqrt{\kappa^2 t^2 + 1} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \frac{\sqrt{2\kappa} \sinh(2\kappa\tau)}{2\sqrt{\cosh(2\kappa\tau) + 1}} \\ \kappa \cosh(\kappa\tau) \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ \kappa \\ 0 \\ 0 \end{bmatrix}, \quad (2.12)$$

At small speeds the Lorentz boost matrix reduces to the identity matrix: this implies $kt \simeq k\tau \simeq 0$. In this case we obtain the same results of the rest frame of the particle for both acceleration and speed.

2.2 Fixed target collision

2.2.1 Center of mass momenta

In the CoM frame, the momenta of the two protons are respectively $(E_p, \pm p, 0, 0)^\top = m_p(\gamma, \pm v, 0, 0)$, where $E_p^2 = m_p^2 + p^2$. The total CoM energy is $-(p_A^\mu + p_B^\mu)^2 = 2m_p^2$.

2.2.2 Center of mass velocity

The momentum of particle B will be given by $p^\mu = m_p u^\mu = (m_p \gamma, m_p \gamma v, 0, 0)^\top$. Therefore, $\gamma v = p/m_p$. Solving this we get:

$$v = \frac{p}{m_p} \sqrt{\frac{1}{(p/m_p)^2 + 1}} = \frac{p}{E_p}, \quad (2.13)$$

2.2.3 Lab frame momenta

The momentum of particle B in its own rest frame will just be $(m_p, 0, 0, 0)^\top$. The momentum of particle A instead will be given by a boost in the x direction with velocity $-v$:

$$(p_A^\mu)_{\text{lab}} = \begin{bmatrix} \gamma & v\gamma & 0 & 0 \\ v\gamma & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} E_p \\ p \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} \gamma E_p + v\gamma p \\ v\gamma E_p + \gamma p \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} m_p \gamma^2 (1 + v^2) \\ 2\gamma p \\ 0 \\ 0 \end{bmatrix}, \quad (2.14)$$

2.3 Weak field gravitational time dilation

2.3.1 Time dilation expression

It is more intuitive geometrically to deal with a pulse sent from A to B , for which we expect the time dilation to work in the opposite sense:

$$\Delta t_B = \Delta t_A (1 + gh), \quad (2.15)$$

up to first order in gh and $g\Delta t_A$, since $(1 + gh)(1 - gh) = 1 - (gh)^2 = 1$ to first order in gh . Alternatively, one can just map $g \rightarrow -g$ to recover the time contraction for pulses sent in the other direction.

We know that the paths of the observers are two curves of constant acceleration: we know their explicit expression from equation (2.1), and additionally we assume that they are separated by a space interval h :

$$x_A(t) = \frac{\sqrt{1 + (gt)^2} - 1}{g} \quad (2.16a)$$

$$x_B(t) = \frac{\sqrt{1 + (gt)^2} - 1}{g} + h. \quad (2.16b)$$

At $t = 0$ Alice sends a pulse, which then reaches Bob at a time t_1 . After a time Δt_A , she sends another, which then reaches Bob at a time t_2 . Right now, we are referring to all times as measured in the rest frame of Alice at $t = 0$. These times can be found by imposing that the space and time separation between the events of the pulse being sent and received are equal, since it travels at light speed: the equations which represent this are $x_B(t_1) = t_1$ and $x_B(t_2) - x_A(\Delta t_A) = t_2 - \Delta t_A$. Substituting the expressions for the positions:

$$t_1 = \frac{\sqrt{1 + (gt_1)^2} - 1}{g} + h \quad (2.17a)$$

$$t_2 - \Delta t_A = \frac{\sqrt{1 + (gt_2)^2} - 1}{g} + h - \left(\frac{\sqrt{1 + (g\Delta t_A)^2} - 1}{g} \right). \quad (2.17b)$$

Now, it is just a matter of calculation to solve these equations, expand up to first order in the adimensional parameters gh and $g\Delta t_A$ and one recovers the desired expression for $\Delta t_B = t_2 - t_1$.

There is one more consideration to make though: what about the Lorentz time dilation for Bob? This is actually a *second order effect*.

Claim 2.1. *The time interval measured by Bob in his frame at $t \sim t_1$ is the same as the one measured in the rest frame of Alice at $t = 0$ up to first order in gh and $g\Delta t_B$.*

Proof. We perform a Lorentz boost to the velocity of Bob at $t = t_1$: this is given by equation (2.2), and is equal to:

$$v = \frac{gt}{\sqrt{(gt)^2 + 1}}, \quad (2.18)$$

with a Lorentz factor of $\gamma = \sqrt{(gt)^2 + 1}$ (see equation (2.3)).

The temporal separation between the two events is Δt_B , while the spatial separation is $\Delta x_B \approx v\Delta t_B$ to first order. The boost, in the (t, x) plane, looks like:

$$\begin{bmatrix} \Delta t_B \\ \Delta x_B \end{bmatrix}' = \begin{bmatrix} \gamma & -v\gamma \\ -v\gamma & \gamma \end{bmatrix} \begin{bmatrix} \Delta t_B \\ \Delta x_B \end{bmatrix} = \begin{bmatrix} \Delta t_B \left(\sqrt{(gt)^2 + 1} - (gt)^2 / \sqrt{(gt)^2 + 1} \right) \\ -gt\Delta t_B + \sqrt{(gt)^2 + 1}gt\Delta t / \sqrt{(gt)^2 + 1} \end{bmatrix}, \quad (2.19)$$



Figure 2: Visualization of the beams, in the frame where the rocket is stationary as the first beam is being sent. The two curves intersecting the space axis are the tip and tail of the spaceship; the beams being sent from the tail are events C and D , while their reception at the tip are events A and B . Event E is just calculated as $B - A$, to make comparisons with D easier. H and G are computed by tracing the dotted line of points which have the same spacetime interval from the origin as points D and E respectively, and selecting its intersection with the temporal axis: this effectively means finding the proper time separation between the two beams being sent/received.

therefore as we would expect the spatial separation is eliminated, while expanding the factor multiplying the temporal one near $gt = 0$ we get:

$$\sqrt{(gt)^2 + 1} - (gt)^2 / \sqrt{(gt)^2 + 1} = 1 + O((gt)^2), \quad (2.20)$$

which proves our result. \square

2.3.2 Gravitational time dilation

By the equivalence principle, the effects measured in a uniformly accelerating frame at g are the same as those measured in a gravitational field with constant acceleration g . The gravitational field in such a frame is given by $\Phi = gh$, where h is the height (with arbitrary zero point): the result follows.

2.3.3 Twins and gravitation

The gravitational time dilation difference, in absolute value, is given by:

$$\Delta t = t_{\text{elapsed}} \frac{g\Delta h}{c^2} \approx 1 \text{ yr} \frac{10 \text{ m/s}^2 \times 100 \text{ m}}{(3 \times 10^8 \text{ m/s})^2} \approx 3.5 \times 10^{-7} \text{ s}. \quad (2.21)$$

We are asked what is the age of the twin on the ground as measured by the twin who is higher up: this is analogous to the situation considered in the first section of this problem; the twin higher up will measure the twin lower down to be older, specifically if $\text{age}_{\text{up}} = 1 \text{ yr}$, then the observer up in the palace will measure the age of the twin at ground level as:

$$\text{age}_{\text{down}} = 1 \text{ yr} + 3.5 \times 10^{-7} \text{ s} \approx (1 + 1 \times 10^{-14}) \text{age}_{\text{up}}. \quad (2.22)$$

Sheet 3

3.1 Changes of coordinate system

We denote by $x^\mu = (x, y)$ and $x'^\mu = (r, \theta)$. Then, we have the following Jacobian matrices:

$$\frac{\partial x^\mu}{\partial x'^\nu} = \begin{bmatrix} \cos(\theta) & -r \sin(\theta) \\ \sin(\theta) & r \cos(\theta) \end{bmatrix} \quad (3.1a)$$

$$\frac{\partial x'^\nu}{\partial x^\rho} = \begin{bmatrix} \frac{x}{\sqrt{x^2 + y^2}} & \frac{y}{\sqrt{x^2 + y^2}} \\ -\frac{y}{x^2 + y^2} & \frac{x}{x^2 + y^2} \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\frac{\sin(\theta)}{r} & \frac{\cos(\theta)}{r} \end{bmatrix}, \quad (3.1b)$$

which can be found by plain differentiation of the change of coordinates, recalling $(\arctan x)' = 1/(1 + x^2)$. Then, we can compute the product of these two matrices: it comes out to be

$$\frac{\partial x^\mu}{\partial x'^\nu} \frac{\partial x'^\nu}{\partial x^\rho} = \delta_\rho^\mu, \quad (3.2)$$

since on the diagonal we get $\cos^2(\theta) + \sin^2(\theta) = 1$, while on the off-diagonal terms we get a multiple of $\sin(\theta) \cos(\theta) - \sin(\theta) \cos(\theta) = 0$.

Note that relation (3.2) is just the chain rule written in more generality: substituting the explicit coordinates for x^μ and x'^μ we get the desired expression.

3.2 Properties of covariant differentiation

3.2.1 Metric compatibility of the connection

We wish to show that $\nabla_\alpha g_{\mu\nu} = 0$. A very simple way to prove this is by going in the LIF: there, the equation reads $\partial_\alpha \eta_{\mu\nu} = 0$, which is immediately satisfied since

the components of the Minkowski metric are constants. Then, since the equation is tensorial, the result extends to any frame.

This was not the spirit of the exercise, however: let us prove it in a different generic frame. To this end, we define the *Christoffel symbols of the first kind* (while the regular ones are of the second kind):

$$\Gamma_{\mu\nu\rho} = g_{\mu\sigma}\Gamma_{\nu\rho}^{\sigma} = \frac{1}{2}\left(g_{\mu\nu,\rho} + g_{\mu\rho,\nu} - g_{\nu\rho,\mu}\right). \quad (3.3)$$

These are useful since, as all their indices are down, it is easier to study their symmetry properties.

Note that if we antisymmetrize the first and last index, we get $\Gamma_{[\mu|\nu|\rho]} = 1/2g_{\mu\rho,\nu}$ since the first and last terms in the sum cancel (in the latter we must invert the indices ν and ρ in order to see this, but this can always be done by the symmetry of the metric).

Then, we write the expression for the covariant derivative of the metric:

$$\nabla_{\alpha}g_{\mu\nu} = \partial_{\alpha}g_{\mu\nu} - \Gamma_{\mu\alpha}^{\rho}g_{\rho\nu} - \Gamma_{\nu\alpha}^{\rho}g_{\mu\rho} = g_{\mu\nu,\alpha} - \Gamma_{\nu\alpha\mu} - \Gamma_{\mu\alpha\nu}, \quad (3.4)$$

which is just $g_{\mu\nu,\alpha} - 2\Gamma_{[\nu|\alpha|\mu]} = g_{\mu\nu,\alpha} - g_{\nu\mu,\alpha} = 0$, again by the symmetry of the metric.

One could argue that this is the opposite way round: we should *assume* $\nabla_{\mu}g_{\rho\sigma} = 0$ and derive from it the formula that was given for the Christoffel symbols in terms of the partial derivatives of the metric.

3.2.2 Leibniz rule

As before, this can be proved in the LIF from the Leibniz rule of regular partial derivatives.

As before, we like to calculate therefore we show this explicitly in any frame.

The derivative of the tensor product looks like:

$$\nabla_{\mu}\left(A_{\nu\lambda}B_{\rho}\right) = \partial_{\mu}\left(A_{\nu\lambda}B_{\rho}\right) - \Gamma_{\mu\nu}^{\sigma}A_{\sigma\lambda}B_{\rho} - \Gamma_{\mu\lambda}^{\sigma}A_{\nu\sigma}B_{\rho} - \Gamma_{\mu\rho}^{\sigma}A_{\nu\lambda}B_{\sigma}, \quad (3.5)$$

while the sum of derivatives looks like:

$$\begin{aligned} B_{\rho}\nabla_{\mu}A_{\nu\lambda} + A_{\nu\lambda}\nabla_{\mu}B_{\rho} = & B_{\rho}\partial_{\mu}A_{\nu\lambda} - \Gamma_{\mu\nu}^{\sigma}A_{\sigma\lambda}B_{\rho} - \Gamma_{\mu\lambda}^{\sigma}A_{\nu\sigma}B_{\rho} \\ & + A_{\nu\lambda}\partial_{\mu}B_{\rho} - \Gamma_{\mu\rho}^{\sigma}A_{\nu\lambda}B_{\sigma}, \end{aligned} \quad (3.6)$$

so we can see that the Christoffel terms are equal, and the partial derivative terms also are since we have the Leibniz rule for partial derivatives.

3.3 2D Christoffel symbols

3.3.1 Polar coordinates

The metric and inverse metric are respectively given by $g_{\mu\nu} = \text{diag}(1, r^2)$ and $g^{\mu\nu} = \text{diag}(1, r^{-2})$. We only care about the partial derivatives of the lower-indices one, and the only nonvanishing derivative is $g_{11,0} = 2r$, where we mean $(x^0, x^1) = (r, \theta)$.

Then it is tedious but straightforward to perform the direct computation. Things that make it faster are discarding immediately terms which cannot contribute (such as $g_{\alpha\beta,\gamma}$ where at least one of α and β is not 1 or γ is not 0, and only looking at the six independent symbols instead of the eight total ones (since $\Gamma_{01}^\alpha = \Gamma_{10}^\alpha$ for any α).

Then one can see that the nonvanishing symbols are

$$\Gamma_{11}^0 = \frac{1}{2}g^{0\alpha}(g_{\alpha 1,1} + g_{\alpha 1,1} - g_{11,\alpha}) = \frac{1}{2}g^{00}(-g_{11,0}) = -\frac{2r}{2} = -r \quad (3.7a)$$

$$\Gamma_{01}^1 = \frac{1}{2}g^{1\alpha}(g_{\alpha 0,1} + g_{\alpha 1,0} - g_{01,\alpha}) = \frac{1}{2}g^{11}g_{11,0} = \frac{1}{2}\frac{1}{r^2}2r = \frac{1}{r}. \quad (3.7b)$$

3.3.2 Spherical surface

Now we have the following metric and inverse metric:

$$g_{\mu\nu} = \begin{bmatrix} R^2 & 0 \\ 0 & R^2 \sin^2(\theta) \end{bmatrix}, \quad g^{\mu\nu} = \begin{bmatrix} R^{-2} & 0 \\ 0 & R^{-2} \sin^{-2}(\theta) \end{bmatrix}, \quad (3.8)$$

but do note that R is a constant: given $(x^0, x^1) = (\theta, \varphi)$, we have as before that the only nontrivial derivative is $g_{11,0} = 2R^2 \sin(\theta) \cos(\theta)$.

Then this case is exactly analogous to the previous one: the same symbols are zero, so we can skip almost all of the computation and jump straight to:

$$\Gamma_{11}^0 = -\frac{1}{2}g^{00}g_{11,0} = -\sin(\theta) \cos(\theta) \quad (3.9a)$$

$$\Gamma_{01}^1 = \frac{1}{2}g^{11}g_{11,0} = \frac{\cos(\theta)}{\sin(\theta)}. \quad (3.9b)$$

3.4 Parallel transport

We know from the last exercise the metric and Christoffel symbols of 2D space and of the surface of a sphere.

The equations of parallel transport are in general $u^\mu \nabla_\mu V^\nu = 0$.

3.4.1 Flat space

We want to determine the behaviour of a vector field $V^\mu(\theta)$ defined on a curve $x^\mu(\theta) = (R, \theta)$ with fixed R , such that $V^\mu(\theta = 0) = (0, 1/R)$ (a unit vector: $V^\mu(0)V^\nu(0)g_{\mu\nu}(0) = 1$).

In our case the tangent vector of the curve is $u^\mu = (0, 1)$. Therefore the equations simplify to:

$$\nabla_1 V^\mu = \partial_1 V^\mu + \Gamma_{1\alpha}^\mu V^\alpha = 0, \quad (3.10)$$

which are two coupled differential equations; we can make them explicit and substitute the Christoffel symbols found earlier.

$$\nabla_1 V^0 = \partial_1 V^0 + \cancel{\Gamma_{10}^0 V^0} + \Gamma_{11}^0 V^1 = \partial_1 V^0 - r V^1 \quad (3.11a)$$

$$\nabla_1 V^1 = \partial_1 V^1 + \Gamma_{10}^1 V^0 + \cancel{\Gamma_{11}^1 V^1} = \partial_1 V^1 + \frac{1}{r} V^0, \quad (3.11b)$$

so we can write this linear system like:

$$\partial_1 \begin{bmatrix} V^0 \\ V^1 \end{bmatrix} = \begin{bmatrix} 0 & r \\ -r^{-1} & 0 \end{bmatrix} \begin{bmatrix} V^0 \\ V^1 \end{bmatrix}. \quad (3.12)$$

The eigenvalues of this matrix are $\pm i$, so its exponential is a pure rotation matrix:

$$\exp\left(\theta \begin{bmatrix} 0 & r \\ -r^{-1} & 0 \end{bmatrix}\right) = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} = R(-\theta), \quad (3.13)$$

so the solution is

$$V^\mu(\theta) = R(-\theta)V^\mu(0). \quad (3.14)$$

This means that our vector is rotating clockwise with unit angular velocity in the (r, θ) plane, just as the point it is defined at moves counterclockwise with unit angular velocity: therefore, if we look at the vector in Cartesian coordinates, we will see it always aligned with its initial direction and the same modulus.

Specifically, when $\theta = \pi/2$ we get $V^\mu = (1, 0)$: this has the same modulus as $(0, 1/R)$ since we compute lengths with respect to the metric of our space, as $\|V\|^2 = V^\mu V^\nu g_{\mu\nu}$.

Another way to solve (3.12) is to explicit from the second equation $V^0 = -r\partial_1 V^1$ and plug it into the second, so that it becomes

$$\partial_1(-r\partial_1 V^1) = V^1, \quad (3.15)$$

which leads to the same result.

3.4.2 Curved space: spherical surface

Now our curve is $x^\mu(\theta) = (\theta, 0)$ in the spherical coordinates $x^\mu = (\theta, \varphi)$. The metric is the one given in (3.8), the Christoffel symbols are the ones given in (3.9).

The parallel transport equations are now:

$$\nabla_1 V^0 = \partial_0 V^0 + \cancel{\Gamma_{00}^0 V^0} + \cancel{\Gamma_{01}^0 V^1} \quad (3.16a)$$

$$\nabla_1 V^1 = \partial_0 V^1 + \cancel{\Gamma_{00}^1 V^0} + \Gamma_{01}^1 V^1 = \partial_0 V^1 + \frac{V^1}{\tan(\theta)}. \quad (3.16b)$$

The first equation gives us $V^1 = \text{const}$, while we do not need to actually solve the second one: our initial condition is $V^\mu(\theta = 0) = (R^{-1}, 0)$, and $V^1 \equiv 0$ is a solution to that first-order equation, so by the uniqueness we have found the whole solution.

Therefore the vector is constant in these coordinates.

Specifically, at $\theta = \pi/2$ we get $V^\mu = (1/R, 0)$.

Sheet 4

4.1 Riemann tensor computations

4.1.1 LIF form

In the LIF, we have $g_{\mu\nu} = \eta_{\mu\nu}$ and $g_{\mu\nu,\alpha} = 0$. Therefore, the Christoffel symbols are all zero. In the explicit expression of the Riemann tensor, which looks like $R = \partial\Gamma + \Gamma\Gamma$ we can drop the second term and keep only the derivatives of the Christoffel symbols, which are nonzero since they depend on the second derivatives of the metric.

If the Christoffel symbols are zero, the computation of the curvature tensor is significantly easier, since we do not have the $\Gamma\Gamma$: we just need to account for the terms $\partial\Gamma$. The computation gives:

$$R_{\nu\rho\sigma}^\mu = 2\partial_{[\rho}\Gamma_{\sigma]\nu}^\mu \quad (4.1a)$$

$$= 2\partial_{[\rho}\left(\frac{1}{2}g^{\mu\alpha}\left(g_{\alpha|\sigma],\nu} + g_{\alpha\nu,|\sigma]} - g_{\nu|\sigma],\alpha}\right)\right) \quad (4.1b)$$

$$= g^{\mu\alpha}\left(g_{\alpha[\sigma],\nu|\rho]} + \cancel{g_{\alpha\nu,|\sigma]\rho]} - g_{\nu[\sigma],\alpha|\rho]}\right), \quad (4.1c)$$

where a term was cancelled since it contained the antisymmetrization of partial derivatives, which commute.

So, if we lower the index of the (1, 3) Riemann tensor we get the desired expression for the all-lower (0, 4) Riemann tensor:

$$R_{\mu\nu\rho\sigma} = g_{\mu[\sigma],\nu|\rho]} - g_{\nu[\sigma],\mu|\rho]}. \quad (4.2)$$

4.1.2 Ricci tensor and scalar

The Ricci tensor is given by:

$$R_{\mu\nu} = R_{\mu\alpha\nu}^{\alpha} = g^{\alpha\beta} R_{\alpha\mu\beta\nu} = g^{\alpha\beta} \left(g_{\alpha[\nu|\mu|\beta]} - g_{\mu[\nu|\alpha|\beta]} \right). \quad (4.3)$$

So we have

$$R_{\mu\nu} = \frac{1}{2} g^{\alpha\beta} \left(g_{\alpha\nu,\mu\beta} - g_{\alpha\beta,\mu\nu} - g_{\mu\nu,\alpha\beta} + g_{\mu\beta,\alpha\nu} \right) \quad (4.4a)$$

$$= \frac{1}{2} g^{\alpha\beta} \left(2g_{\alpha(\nu,\mu)\beta} - g_{\mu\nu,\alpha\beta} - g_{\alpha\beta,\mu\nu} \right) \quad (4.4b)$$

$$= g_{\alpha(\nu,\mu)}^{\alpha} - \frac{1}{2} \square g_{\mu\nu} - \frac{1}{2} g^{\alpha\beta} g_{\alpha\beta,\mu\nu}, \quad (4.4c)$$

where¹ the square \square denotes the D'Alembert operator, $\square = \partial_\beta \partial^\beta = g^{\alpha\beta} \partial_\alpha \partial_\beta$.

The Ricci scalar, on the other hand, is given by

$$R = g^{\mu\nu} R_{\mu\nu} = g^{\mu\nu} g_{\alpha(\nu,\mu)}^{\alpha} - g^{\mu\nu} \square g_{\mu\nu} - g^{\alpha\beta} \square g_{\alpha\beta} = (g_{\alpha\nu}^{\alpha\nu} - g^{\mu\nu} \square g_{\mu\nu}), \quad (4.5)$$

where we identified the two terms containing the metric contracted with its d'Alembertian, since they are equal up to a relabeling of indices.

We neglected the symmetrization in the first term since when contracting with the metric the indices $\mu\nu$ are automatically symmetrized.

4.1.3 LIF identities

$$\nabla_\alpha \left(R_\beta^\alpha - \frac{R}{2} \delta_\beta^\alpha \right) = \partial_\alpha \left(g^{\alpha\lambda} R_{\lambda\beta} - \frac{R}{2} \delta_\beta^\alpha \right) \quad (4.6a)$$

$$= \eta^{\alpha\lambda} R_{\lambda\beta,\alpha} - \frac{1}{2} R_{,\beta}, \quad (4.6b)$$

since in the LIF the metric is the Minkowski one, and the Christoffel symbols are zero therefore $\nabla_\alpha = \partial_\alpha$.

4.1.4 Contracted Bianchi identities

The first term is

$$\eta^{\beta\mu} R_{\mu\nu,\beta} = \eta^{\beta\mu} \left(2g_{\alpha(\nu,\mu)}^{\alpha} - \square g_{\mu\nu} - g^{\alpha\beta} g_{\alpha\beta,\mu\nu} \right)_{,\beta}, \quad (4.7)$$

¹All the indices after the comma are derivatives, even when they become upper.

which we can expand out: the Minkowski metric raises the derivative with respect to x^β and turns it into a derivative with respect to x_μ , and we can also expand the D'Alambertian and the symmetrization: we get

$$\eta^{\beta\mu} R_{\mu\nu,\beta} = g_{\alpha\nu,\mu}{}^{\alpha\mu} + g_{\alpha\mu,\nu}{}^{\alpha\mu} - g_{\mu\nu,\alpha}{}^{\alpha\mu} - g^{\alpha\beta} g_{\alpha\beta,\mu\nu}{}^\mu \quad (4.8a)$$

$$= +g_{\alpha\mu,\nu}{}^{\alpha\mu} - \left(g^{\alpha\beta} \square g_{\alpha\beta} \right)_{,\nu} \quad (4.8b)$$

$$= \partial_\nu \left(g_{\mu\alpha}{}^{,\mu\alpha} - g^{\alpha\beta} \square g_{\alpha\beta} \right), \quad (4.8c)$$

since, up to a relabeling of indices, the first and third term in (4.8a) are equal.

The derivative $\partial_\nu R$, on the other hand, is twice that:

$$\partial_\nu R = \partial_\nu \left(2g_{\mu\alpha}{}^{,\mu\alpha} - 2g^{\alpha\beta} \square g_{\alpha\beta} \right), \quad (4.9)$$

as can be directly gathered from (4.5).

Therefore, the quantity in (4.6b) is zero.

4.1.5 Alternative expression

Since the metric is covariantly constant, we can just bring it inside the derivative:

$$0 = g^{\beta\mu} \nabla_\alpha \left(R^\alpha{}_\mu - \frac{1}{2} R \delta^\alpha_\mu \right) = \nabla_\alpha \left(R^{\alpha\beta} - \frac{1}{2} R g^{\alpha\beta} \right). \quad (4.10)$$

These are called the *Contracted Bianchi identities*, and can be alternatively derived from the Bianchi identities of the Riemann tensor, $R_{\mu\nu[\rho\sigma;\alpha]} = 0$.

4.2 Properties of the Ricci tensor

4.2.1 Symmetry generality

The fact that $T^{\mu\nu} = T^{\nu\mu}$ is frame invariant could be derived plainly from the fact that it is a tensor equation; to be more explicit we can say that under a change of coordinates with Jacobian matrix Λ we have $\tilde{T}^{\mu\nu} = \Lambda^\mu{}_\alpha \Lambda^\nu{}_\beta T^{\alpha\beta}$; when written in components like this the Jacobians commute, therefore we can just interchange them for both $\tilde{T}^{\mu\nu}$ and $\tilde{T}^{\nu\mu}$ to recover their equality.

4.2.2 Symmetry of the Ricci tensor.

The expression (4.4c) is manifestly symmetric: part of it is explicitly symmetrized, part is proportional to the metric, which is symmetric.

Therefore, the Ricci tensor is symmetric in any frame.

4.3 Weak field Einstein equations

We consider the *weak field* case, when $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ with $|h_{\mu\nu}| \ll 1$. We will then neglect second and higher order terms in $h_{\mu\nu}$.

4.3.1 The gravitational potential

We want to work towards Newton's equation, which is $\nabla^2\Phi = 4\pi G_N\rho$, where Φ is the gravitational potential. What defines the gravitational potential is² its effect on test masses: they accelerate with $\vec{a} = -\vec{\nabla}\Phi$.

What is the relativistic equivalent of this? A particle in GR follows a geodesic, a curve without proper acceleration. Proper acceleration is a four-vector defined by $a^\mu = u^\nu \nabla_\nu u^\mu$. If the four-velocity of a particle is u^μ , then for it the equation of geodesic motion reads:

$$0 = a^\mu = u^\nu \partial_\nu u^\mu + \Gamma_{\nu\alpha}^\mu u^\nu u^\alpha, \quad (4.11)$$

which can be written in terms of derivatives with respect to proper time:

$$0 = \frac{d^2 x^\mu}{ds^2} + \Gamma_{\nu\alpha}^\mu u^\nu u^\alpha. \quad (4.12)$$

If the speeds are much less than that of light, this can be approximated: $s \approx t$, and the only terms which contributes to order 0 in v in the Christoffel symbol sum is the one with $u^0 u^0 \approx 1$: in the end then we get for the spatial components:

$$0 = \frac{d^2 x^i}{dt^2} + \Gamma_{00}^i, \quad (4.13)$$

so we can see that the main contribution in the low-speed limit to the (coordinate!) acceleration of the particle are the symbols Γ_{00}^i . The expression for these in terms of the perturbed metric is:

$$\Gamma_{00}^i = \frac{1}{2} \eta^{i\alpha} (2h_{\alpha 0,0} - h_{00,\alpha}) = -\frac{1}{2} h_{00}{}^{,i} = -\frac{1}{2} \vec{\nabla}^i h_{00}, \quad (4.14)$$

if we assume stationarity of the metric (which is justified if we are treating a problem such as the gravitational pull on a body on the surface of the Earth) at least up to first order in h .

Putting everything together: we found that

$$\frac{d^2 x^i}{dt^2} = \frac{1}{2} \vec{\nabla}^i h_{00}, \quad (4.15)$$

²In the lecture notes this is solved differently: instead of finding the gravitational potential from the equation of geodesic motion, there it is found by identification of the gravitational redshift.

but the equation which defines the gravitational field is

$$\frac{d^2 x^i}{dt^2} = -\vec{\nabla}^i \Phi, \quad (4.16)$$

therefore, in the low-gravitational field and low-speed limit, we must identify $h_{00} = -2\Phi$.

4.3.2 Reframing the EFE

We can contract the EFE with the inverse metric, recalling that $g^{\mu\nu}g_{\mu\nu} = 4$, to get $-R = 8\pi G_N T$. Therefore, they can be reframed by substituting the curvature scalar term with the trace of the stress-energy tensor:

$$R_{\mu\nu} = 8\pi G_N \left(T_{\mu\nu} - \frac{1}{2} T g_{\mu\nu} \right). \quad (4.17)$$

This will aid us by reducing the number of difficult curvature tensors to compute.

In the low-speed, weak-field limit matter has negligible pressure and is mostly just travelling in the time direction. Therefore, we approximate the stress energy tensor as that of noninteracting dust: $T^{\mu\nu} = \rho u^\mu u^\nu$. In our frame matter is almost stationary, therefore we have that $T_{00} \approx T^{00} \eta_{00} \eta_{00} \approx \rho$. The trace of the curvature tensor is instead approximately $T \approx T^{00} \eta_{00} \approx -\rho$.

In the end, the 00 component of the equations reads:

$$R_{00} = 8\pi G_N \left(\rho - \frac{1}{2} (-\rho) \eta_{00} \right) = 4\pi G_N \rho. \quad (4.18)$$

Now we only need to show that $R_{00} = \nabla^2 \Phi$.

4.3.3 The derivatives in the curvature tensor

The component we need to calculate is $R_{00} = R_{0\mu 0}^\mu = R_{0i 0}^i$ by antisymmetry.

Let us recall here the general expression for the Riemann tensor:

$$R_{\nu\rho\sigma}^\mu = 2\Gamma_{[\nu|\sigma,|\rho]}^\mu + 2\Gamma_{\sigma[\nu}^\alpha \Gamma_{\rho]\alpha}^\mu. \quad (4.19)$$

In our case, this simplifies to

$$R_{0i 0}^i = \Gamma_{00,i}^i - \Gamma_{i0,0}^i + \Gamma_{00}^\alpha \Gamma_{i\alpha}^i - \Gamma_{0i}^\alpha \Gamma_{0\alpha}^i. \quad (4.20)$$

The second term contains time derivatives, which we decided to neglect by dealing with the stationary case. The third and fourth term are of second order in h .

The only remaining term is the first one: using the expression (4.14) and the identification $h_{00} = -2\Phi$, it is

$$R_{00} = \Gamma_{00,i}^i = \left(-\frac{1}{2} \partial^i h_{00} \right)_{,i} = \partial_i \partial^i \Phi, \quad (4.21)$$

which is what we wanted to prove.

Sheet 5

5.1 Alternative derivation of the contracted Bianchi identities

The form of the Riemann tensor in a LIF was derived in section 4.1.1.

5.1.1 Bianchi identities of the Riemann tensor

In the LIF, given that $R_{\mu\nu\rho\sigma} = g_{\mu[\sigma|\nu|\rho]} - g_{\nu[\sigma|\mu|\rho]}$, we want to show that $R_{\mu\nu[\rho\sigma;\alpha]} = R_{\mu\nu[\rho\sigma;\alpha]} = 0$.

This is equivalent to the formulation of the Bianchi identities given in the problem sheet, because of the antisymmetry of the Riemann tensor in its last two indices: there are six terms in the antisymmetrization of $R_{\mu\nu[\rho\sigma;\alpha]}$, but they are pairwise equal: the term $R_{\mu\nu\rho\sigma;\alpha}$ is equal to $-R_{\mu\nu\sigma\rho;\alpha}$ by antisymmetry, and these are exactly the pairs of terms which appear in the three-index antisymmetrization.

What we need to do is to take the derivative of the Riemann tensor in the LIF:

$$R_{\mu\nu\rho\sigma;\alpha} = g_{\mu[\sigma|\nu|\rho]\alpha} - g_{\nu[\sigma|\mu|\rho]\alpha}, \quad (5.1)$$

and permute the three indices $\rho\sigma\alpha$ cyclically. Writing all the terms out we get (up to a factor 2, which is irrelevant since we will find that all the terms cancel and everything is equal to 0):

$$\begin{aligned} & +g_{\mu\sigma;\nu\rho\alpha} - g_{\nu\sigma;\mu\rho\alpha} - g_{\mu\rho;\nu\sigma\alpha} + g_{\nu\rho;\mu\sigma\alpha} + \\ & +g_{\mu\alpha;\nu\sigma\rho} - g_{\nu\alpha;\mu\sigma\rho} - g_{\mu\sigma;\nu\alpha\rho} + g_{\nu\sigma;\mu\alpha\rho} + \\ & +g_{\mu\rho;\nu\alpha\sigma} - g_{\nu\rho;\mu\alpha\sigma} - g_{\mu\alpha;\nu\rho\sigma} + g_{\nu\alpha;\mu\rho\sigma}, \end{aligned} \quad (5.2)$$

so we have 6 terms with a + sign, and 6 with a - sign: they cancel pairwise, since the partial derivatives commute.

5.1.2 Contracting the identities

We start by contracting $2R_{\mu\nu[\rho\sigma;\alpha]}$ with $g^{\mu\rho}$: we get

$$0 = g^{\mu\rho} (R_{\mu\nu\rho\sigma;\alpha} + R_{\mu\nu\alpha\rho;\sigma} + R_{\mu\nu\sigma\alpha;\rho}) = R_{\nu\sigma;\alpha} - R_{\nu\alpha;\sigma} + g^{\mu\rho} R_{\mu\nu\sigma\alpha;\rho}, \quad (5.3)$$

where, in the second term, we used the antisymmetry of the first two indices of the Riemann tensor in order to get the form which allowed us to use the definition of the Ricci tensor $R_{\mu\nu} = g^{\rho\sigma} R_{\rho\mu\sigma\nu}$. Also, we brought the metric inside the covariant derivatives since it is covariantly constant. Then, we contract the expression we found with $g^{\nu\sigma}$:

$$0 = g^{\nu\sigma} (R_{\nu\sigma;\alpha} - R_{\nu\alpha;\sigma} + g^{\mu\rho} R_{\mu\nu\sigma\alpha;\rho}) = R_{;\alpha} - R^{\sigma}_{\alpha;\sigma} - g^{\mu\rho} R_{\mu\alpha;\rho} \quad (5.4)$$

$$= R_{;\alpha} - R^{\sigma}_{\alpha;\sigma} - R^{\sigma}_{\alpha;\sigma}, \quad (5.5)$$

where we used the same properties as before and the definition of the scalar curvature $R = g^{\mu\nu} R_{\mu\nu}$. So, we have the contracted Bianchi identities $0 = R_{;\alpha} - 2R^{\sigma}_{\alpha;\sigma}$. Raising an index with the inverse metric $g^{\alpha\beta}$ and relabeling σ to α in the second term (after having raised the index), these can be written as

$$\nabla_{\alpha} (Rg^{\alpha\beta} - 2R^{\alpha\beta}). \quad (5.6)$$

5.2 Weak-field geodesic equation

This was already treated in section 4.3.1.

5.3 Hyperbolic plane geodesics

Our coordinates are (x, y) , and our metric is $g_{ij} = y^{-2}\delta_{ij}$, with inverse $g^{ij} = y^2\delta^{ij}$.

So, we can calculate the Christoffel symbols as:

$$\Gamma_{jk}^i = \frac{1}{2}g^{im} (g_{mj,k} + g_{mk,j} - g_{jk,m}), \quad (5.7)$$

this calculation is simplified by the fact that the only nonvanishing derivatives of the metric are $g_{00,1} = g_{11,1} = -2y^{-3}$. If the index i in Γ_{jk}^i is zero, then the last term in the sum vanishes since it corresponds to a derivative with respect to x . With these we get:

$$\Gamma_{00}^0 = \frac{1}{2}y^2(2g_{00,0}) = 0 \quad (5.8a)$$

$$\Gamma_{01}^0 = \frac{1}{2}y^2(g_{00,1}) = -\frac{1}{y} \quad (5.8b)$$

$$\Gamma_{11}^0 = \frac{1}{2}y^2(g_{01,1} + g_{01,1}) = 0 \quad (5.8c)$$

$$\Gamma_{00}^1 = \frac{1}{2}y^2(-g_{00,1}) = \frac{1}{y} \quad (5.8d)$$

$$\Gamma_{01}^1 = \frac{1}{2}y^2(g_{10,0} + g_{11,0} - g_{01,1}) = 0 \quad (5.8e)$$

$$\Gamma_{11}^1 = \frac{1}{2}y^2(g_{11,1} + g_{11,1} - g_{11,1}) = -\frac{1}{y}, \quad (5.8f)$$

and the geodesic equation $u^{\mu}\nabla_{\mu}u^{\nu} = 0$ is written with respect to these.

5.3.1 Vertical lines

First of all we want to parametrize these vertical lines: we choose our parameter so that the length of the velocity vector is everywhere equal to one.

Since the lines are vertical, we want the position x^i with respect to the parameter s to look something like $x^i(s) = (x_0, y(s))$.

We use the arclength parameter:

$$s = \int \sqrt{g_{ij}u^i u^j} d\lambda, \quad (5.9)$$

where $u^i = dx^i/d\lambda$ and λ is an arbitrary parameter.

We can rewrite this integral with respect to the Euclidean norm $\|u\|_E^2 = \delta_{ij}u^i u^j$: we get

$$s = \int \frac{1}{y} \|u\|_E d\lambda, \quad (5.10)$$

so we can see that we get $s = \int d\lambda$, or $s = \lambda$, iff $\|u\|_E = y$: so, let us drop the distinction between s and λ and apply this condition. The velocity vector is

$$u^i = \frac{dx^i}{ds} = \left(0, \frac{dy}{ds}\right), \quad (5.11)$$

whose Euclidean norm is just (the absolute value of) dy/ds . So, we must impose the condition $y = dy/ds$, which can be solved by separation of variables to yield $s = \log y$, or $y = e^s$.

So our parametrization for the curve is $s \rightarrow x^i = (x_0, e^s)$, the velocity is $u^i = (0, e^s)$ and the derivative of velocity with respect to s is again

$$\frac{du^i}{ds} = (0, e^s). \quad (5.12)$$

Now we can plug these into our geodesic equation, which is simplified by the fact that $u^0 = 0$, therefore there is only one relevant term in the Christoffel sum:

$$\frac{du^i}{ds} + \Gamma_{11}^i u^1 u^1 = 0, \quad (5.13)$$

whose components are

$$\underbrace{\frac{du^0}{ds}}_0 + \underbrace{\Gamma_{11}^0}_0 y^2 = 0 \quad (5.14)$$

and

$$\frac{du^1}{ds} + \Gamma_{11}^1 u^1 u^1 = 0 \quad (5.15a)$$

$$y + \left(-\frac{1}{y}\right) y^2 = 0, \quad (5.15b)$$

which are identities, therefore vertical lines are indeed geodesics in this hyperbolic plane.

5.3.2 More solutions

We have the Killing vector field $\xi = (1, 0)$ corresponding to the symmetry with respect to translations along the x axis: then, the quantity $\vec{\xi} \cdot \vec{u}$ is conserved: so $\xi^\mu u^\nu g_{\mu\nu} = \dot{x}g_{00} = \dot{x}y^{-2}$ is constant along the trajectory (here we denote derivatives with respect to the parameter s by a dot).

We also know that, if we parametrize with arclength, $\|u\|_E/y \equiv 1$, which means

$$y = \|u\|_E = \sqrt{\dot{x}^2 + \dot{y}^2} = \dot{x}\sqrt{(y')^2 + 1}, \quad (5.16)$$

where $y' = dy/dx = \dot{y}/\dot{x}$.

Then, the conserved quantity can be rewritten as

$$\dot{x}y^{-2} = y^{-2} \frac{y}{\sqrt{y'^2 + 1}} = \frac{1}{y\sqrt{y'^2 + 1}}, \quad (5.17)$$

which the exercise sheet calls A but I will call it $1/R$: so $R = y\sqrt{y'^2 + 1}$. We can square this to write the conservation equation

$$y^2(y'^2 + 1) = R^2 = \text{const.} \quad (5.18)$$

Alternatively, once one has found the equations of motion

$$y\ddot{y} = \dot{y}^2 - \dot{x}^2 \quad (5.19a)$$

$$y\ddot{x} = 2\dot{x}\dot{y}, \quad (5.19b)$$

to prove the constancy of $\dot{x}y^{-2}$ one can observe that

$$y^2 \frac{d}{ds} \left(\frac{\dot{x}}{y^2} \right) = \ddot{x} - 2 \frac{\dot{x}\dot{y}}{y}, \quad (5.20)$$

so $\dot{x}y^{-2}$ being a constant is equivalent to the second equation of motion holding.

5.3.3 Solving the equation

The equation $y^2(y'^2 + 1) = R^2$ can be rewritten as

$$\frac{dy}{dx} = \pm \sqrt{\frac{R^2}{y^2} - 1}, \quad (5.21)$$

which means that if we fix R the value of the derivative of the curve can only attain two opposite values. Do note that we can go from one branch to the other with the

transformation $x \rightarrow -x$, a mirror symmetry around some center. Then, we can just make the gauge choice $y' > 0$ and integrate by separation of variables:

$$\int \frac{y \, dy}{\sqrt{R^2 - y^2}} = \int dx, \quad (5.22)$$

which can be solved with the substitution $y = R \sin(\theta)$, with $dy = R \cos(\theta) d\theta$. Inserting this, we find:

$$x - x_0 = \int \frac{R \sin \theta R \cos \theta \, d\theta}{R \sqrt{1 - \sin^2 \theta}} = R \int \sin \theta \, d\theta = -R \cos \theta, \quad (5.23)$$

which can be squared to find $(x - x_0)^2 = R^2(1 - \sin^2 \theta) = R^2 - y^2$, or

$$R^2 = (x - x_0)^2 + y^2, \quad (5.24)$$

the equation of a circle. We can then confirm that this solution also holds in the other branch, up to a change of integration constant, by rewriting $(x - x_0)^2 = ((-x) - x_1)^2$: this is solved by $x_0 = -x_1$.

Geometrically, we are looking at circles with origins on the x axis and radius R . If y and R are fixed, then there are only two possible circles, which can be found by connecting a certain point at height y to the x axis with a segment of length R . One can then see that the right halves of the circles we found can be found from the left halves by symmetry.

Sheet 6

6.1 Sphere pole Riemann coordinates

Recall from section 3.3.2 the spherical surface metric in the coordinates (θ, φ) :

$$g_{\mu\nu} = \begin{bmatrix} R^2 & 0 \\ 0 & R^2 \sin^2 \theta \end{bmatrix}, \quad (6.1)$$

and the Christoffel symbols, which are all zero except for $\Gamma_{11}^0 = -\sin \theta \cos \theta$ and $\Gamma_{01}^1 = \Gamma_{10}^1 = 1/\tan \theta$.

We can plug these into the geodesic equation $u^\mu \nabla_\mu u^\nu$, which comes out to be

$$\ddot{\theta} = +\dot{\varphi}^2 \sin \theta \cos \theta \quad (6.2a)$$

$$\ddot{\varphi} = -2 \frac{\dot{\varphi} \dot{\theta}}{\tan(\theta)}, \quad (6.2b)$$

for a trajectory $(\theta(s), \varphi(s))$ with velocity $(\dot{\theta}, \dot{\varphi})$: dots denote derivatives with respect to s .

Now, we want to check whether parallels and meridians are geodesics. First of all, we want to choose a parameter such that the velocity is of constant norm 1: the equation to satisfy is

$$R^2 \begin{bmatrix} \dot{\theta} & \dot{\varphi} \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & \sin^2 \theta \end{bmatrix} \begin{bmatrix} \dot{\theta} \\ \dot{\varphi} \end{bmatrix} \equiv 1, \quad (6.3)$$

or $\dot{\theta}^2 + \dot{\varphi}^2 \sin^2 \theta = R^{-2}$. Meridians have constant φ : for them, then, $\dot{\theta}^2 = R^{-2}$, so an appropriate parametrization is $(\theta(s), \varphi(s)) = (s/R, \varphi_0)$. Parallels have constant θ : by an analogous line of reasoning, we parametrize them as $(\theta(s), \varphi(s)) = (\theta_0, s/R \sin \theta)$.

One can readily check that for meridians both of the geodesic equations are identities, while for parallels the second one is an identity but the first reads $0 = \cos \theta / \sin \theta$: it can only be satisfied if $\theta = \pi/2$. This makes sense: geodesics on a sphere are great circles, and the only parallel which is a great circle is the equator.

6.1.1 Riemann coordinates

The coordinates we wish to use are

$$x = R\theta \cos \varphi \quad (6.4a)$$

$$y = R\theta \sin \varphi. \quad (6.4b)$$

They are in the form $x^\alpha = \theta n^\alpha$, for vectors $n^\alpha = R(\cos \varphi, \sin \varphi)$. An orthonormal basis for these vectors can be found by selecting $\varphi = 0, \pi/2$.

As we have shown before, the coordinates x^α describe geodesics if we consider them for fixed φ and with parameter θ , since they are meridians.

6.1.2 Metric computation

The metric transforms as

$$g'_{\mu\nu} = \frac{\partial x^\alpha}{\partial x'^\mu} \frac{\partial x^\beta}{\partial x'^\nu} g_{\alpha\beta}, \quad (6.5)$$

so we need the inverse Jacobian, which is expressed in terms of the new coordinates $x'^\mu = (x, y)$ and the old ones $x^\mu = (\theta, \varphi)$:

$$\frac{\partial x^\alpha}{\partial x'^\mu} = \begin{bmatrix} \frac{1}{R} \frac{x}{\sqrt{x^2+y^2}} & \frac{1}{R} \frac{y}{\sqrt{x^2+y^2}} \\ \frac{-y/x^2}{1+(y/x)^2} & \frac{1/x}{1+(y/x)^2} \end{bmatrix}, \quad (6.6)$$

so we get, using the expansion $\sin^2 \theta \sim \theta^2 - \theta^4/3 + O(\theta^6)$ and the identification $R^2 \theta^2 = x^2 + y^2$:

$$g'_{00} = R^2 \left(\frac{\partial x^0}{\partial x'^0} \right)^2 + R^2 \sin^2 \theta \left(\frac{\partial x^1}{\partial x'^0} \right)^2 \quad (6.7a)$$

$$= \frac{x^2}{x^2 + y^2} + R^2 \sin^2 \theta \frac{y^2}{x^4 (1 + (y/x)^2)^2} \quad (6.7b)$$

$$= \frac{1}{x^2 + y^2} \left(x^2 + \frac{R^2 \sin^2 \theta y^2}{x^2 + y^2} \right) \quad (6.7c)$$

$$= 1 - \frac{y^2}{3R^2} + O((x^2 + y^2)y^2), \quad (6.7d)$$

while for the off-diagonal elements $g'_{01} = g'_{10}$:

$$g'_{01} = R^2 \frac{\partial x^0}{\partial x'^0} \frac{\partial x^0}{\partial x'^1} + R^2 \sin^2 \theta \frac{\partial x^1}{\partial x'^0} \frac{\partial x^1}{\partial x'^1} \quad (6.8a)$$

$$= \frac{xy}{x^2 + y^2} + R^2 \sin^2 \theta \left(-\frac{xy}{(x^2 + y^2)^2} \right) \quad (6.8b)$$

$$= \frac{xy}{x^2 + y^2} \left(1 - \frac{R^2 \sin^2 \theta}{x^2 + y^2} \right) \quad (6.8c)$$

$$= \frac{xy}{x^2 + y^2} \left(\frac{(x^2 + y^2)^2}{3R^2(x^2 + y^2)} \right) + O(x^2 + y^2) \quad (6.8d)$$

$$= \frac{xy}{3R^2} + O(x^2 + y^2), \quad (6.8e)$$

and lastly for the element g'_{11} :

$$g'_{11} = R^2 \left(\frac{\partial x^0}{\partial x'^1} \right)^2 + R^2 \sin^2 \theta \left(\frac{\partial x^1}{\partial x'^1} \right)^2 \quad (6.9a)$$

$$= \frac{y^2}{x^2 + y^2} + R^2 \sin^2 \theta \frac{1}{x^2 (1 + (y/x)^2)^2} \quad (6.9b)$$

$$= \frac{1}{x^2 + y^2} \left(y^2 + R^2 \sin^2 \theta \frac{x^2}{x^2 + y^2} \right) \quad (6.9c)$$

$$= 1 - \frac{x^2}{3R^2} + O((x^2 + y^2)x^2). \quad (6.9d)$$

At the north pole $x = y = 0$, so there $g'_{\mu\nu} = \delta_{\mu\nu}$, and all the first derivatives calculated there vanish since there are no first order terms.

6.1.3 Scalar curvature calculation

The expression we have for the scalar curvature in a LIF is given in equation (4.5).

We can evaluate it for $g'_{\mu\nu}$. Do note that the non-differentiated metric can be identified with the identity, and derivatives with upper and lower indices are the same. So, we get:

$$R_{\text{Ric}} = g_{\alpha\nu,}{}^{\alpha\nu} - \delta^{\mu\nu} \square g_{\mu\nu}, \quad (6.10)$$

where the only nonvanishing terms are:

$$g_{\alpha\nu,}{}^{\alpha\nu} = 2 \frac{\partial^2}{\partial x \partial y} \left(\frac{xy}{3R^2} \right) = \frac{2}{3R^2} \quad (6.11)$$

and what was denoted as the D'alambertian before is just the Laplacian: $\square = \delta^{\mu\nu} \partial_\mu \partial_\nu = \partial_{xx}^2 + \partial_{yy}^2$:

$$\delta^{\mu\nu} \square g_{\mu\nu} = \partial_{xx}^2 g_{11} + \partial_{yy}^2 g_{00} = -2 \frac{2}{3R^2}, \quad (6.12)$$

so in the end we get

$$R_{\text{Ric}} = \frac{2}{3R^2} + \frac{4}{3R^2} = \frac{2}{R^2}, \quad (6.13)$$

which means that the curvature decreases as the radius increases, as we might expect.

6.2 Schwarzschild metric curvature

6.2.1 Christoffel symbols

The computation is tedious and not particularly enlightening: we start from the metric ³

$$ds^2 = -A(r) dt^2 + B(r) dr^2 + r^2 (d\theta^2 + \sin^2 \theta d\varphi^2), \quad (6.14)$$

and compute the Christoffel symbols with the usual formula:

$$\Gamma_{\nu\rho}^\mu = \frac{1}{2} g^{\mu\alpha} (g_{\alpha\nu,\rho} + g_{\alpha\rho,\nu} - g_{\nu\rho,\alpha}), \quad (6.15)$$

where fortunately, since the metric is diagonal, we only need to compute one term in the sum (that is, $\mu \equiv \alpha$ always), and the two indices in the metric must be equal in order for the term to not vanish.

³There is a typo in the homework assignment: the coefficients are written as functions of time.

The metric only depends on θ and r , so any derivatives with respect to t and φ are to be discarded.

With this out of the way, we start computing the 40 independent symbols and find that the nonzero ones are (denoting differentiation with respect to r with a prime):

$$\Gamma_{rt}^t = \frac{A'}{2A} \quad \Gamma_{rr}^r = \frac{B'}{2B} \quad (6.16a)$$

$$\Gamma_{tt}^r = \frac{A'}{2B} \quad \Gamma_{r\theta}^\theta = \frac{1}{r} \quad (6.16b)$$

$$\Gamma_{\theta\theta}^r = -\frac{r}{B} \quad \Gamma_{r\varphi}^\varphi = \frac{1}{r} \quad (6.16c)$$

$$\Gamma_{\varphi\varphi}^r = -\frac{r}{B} \sin^2 \theta \quad \Gamma_{\varphi\varphi}^\theta = -\sin \theta \cos \theta \quad (6.16d)$$

$$\Gamma_{\theta\varphi}^\varphi = \frac{\cos \theta}{\sin \theta}. \quad (6.16e)$$

6.2.2 Ricci component

We want to compute $R_{t\mu t}^\mu$, and in order to do so we must find the three components R_{tit}^i with varying i and sum them (here $i = r, \theta, \varphi$), since R_{ttt}^t vanishes by antisymmetry.

In general we have:

$$R_{tit}^i = 2 \left(\Gamma_{[t|t,|i]}^i + \Gamma_{t[t}^\alpha \Gamma_{i]\alpha}^i \right) \quad (6.17a)$$

$$= \Gamma_{tt,i}^i - \cancel{\Gamma_{it,t}^i} + \Gamma_{tt}^\alpha \Gamma_{i\alpha}^i - \Gamma_{ti}^\alpha \Gamma_{t\alpha}^i. \quad (6.17b)$$

Note that the index i is consider not to be summed here, we are writing a formula for the components of the Riemann tensor; although the expression holds when summing over i as well.

So, we can compute this for the specific values of i : for $i = r$ we have

$$R_{trt}^r = \Gamma_{tt,r}^r + \Gamma_{tt}^\alpha \Gamma_{r\alpha}^r - \Gamma_{tr}^\alpha \Gamma_{t\alpha}^r \quad (6.18a)$$

$$= \left(\frac{A'}{2B} \right)' + \frac{A'}{2B} \frac{B'}{2B} - \frac{A'}{2A} \frac{A'}{2B} \quad (6.18b)$$

$$= \frac{A''}{2B} - \frac{A'}{2B^2} B' + \frac{A'}{4B} \left(\frac{B'}{B} - \frac{A'}{A} \right) \quad (6.18c)$$

$$= \frac{A''}{2B} - \frac{A'}{4B} \left(\frac{A'}{A} + \frac{B'}{B} \right), \quad (6.18d)$$

for $i = \theta$ instead

$$R_{t\theta t}^\theta = \cancel{\Gamma_{tt,\theta}^\theta} + \Gamma_{tt}^\alpha \Gamma_{\theta\alpha}^\theta - \cancel{\Gamma_{t\theta}^\alpha} \Gamma_{t\alpha}^\theta \quad (6.19a)$$

$$= \frac{A'}{2B} \frac{1}{r}, \quad (6.19b)$$

and for $i = \varphi$:

$$R_{t\varphi t}^\varphi = \cancel{\Gamma_{tt,\varphi}^\varphi} + \Gamma_{tt}^\alpha \Gamma_{\varphi\alpha}^\varphi - \cancel{\Gamma_{t\varphi}^\alpha} \Gamma_{t\alpha}^\varphi \quad (6.20a)$$

$$= \frac{A'}{2B} \frac{1}{r}, \quad (6.20b)$$

so our final solution is

$$R_{00} = \sum_i R_{0i0}^i = \frac{A''}{2B} - \frac{A'}{4B} \frac{(AB)'}{AB} + \frac{A'}{Br} \quad (6.21)$$

$$= \frac{A''}{2B} - \frac{A'^2}{4AB} - \frac{A'B'}{4B^2} + \frac{A'}{Br}. \quad (6.22)$$

6.3 Schwarzschild geometry orbits

The derivation up to the equation for the perturbed orbit equation is documented in the lecture notes, I might copy it here later, but for now one can find it there.

During the lecture we got up to the first order equation for the perturbation w for the orbit u , written in the form $u(\varphi) = u_c(1 + w(\varphi))$:

$$\frac{d^2 w}{d\varphi^2} = (6GMu_c - 1)w, \quad (6.23)$$

which is in the form $\ddot{w} + \omega^2 w = 0$, for $\omega^2 = 1 - 6GMu_c$. Now, we know that the first order equation must be complemented by the zeroth order one:

$$u_c = \frac{GM}{l^2} + 3GMu_c^2, \quad (6.24)$$

which can be solved for u_c to yield:

$$u_c = \frac{1 \pm \sqrt{1 - 3 \times 4 \frac{G^2 M^2}{l^2}}}{6GM}, \quad (6.25)$$

therefore the square angular velocity of the perturbation's evolution is:

$$\omega^2 = 1 - 6GM \left(\frac{1 \pm \sqrt{1 - 12 \frac{G^2 M^2}{l^2}}}{6GM} \right) = \pm \sqrt{1 - 12 \frac{G^2 M^2}{l^2}}. \quad (6.26)$$

The solution with the minus sign has no meaning for us, since the solution we want to consider must be stable, with positive ω^2 . So, the angular velocity is

$$\omega = \left(1 - 12 \frac{G^2 M^2}{l^2}\right)^{1/4}, \quad (6.27)$$

and we know that angular velocity and period are related by $T = 2\pi/\omega$: therefore we get

$$T = 2\pi \left(1 - 12 \frac{G^2 M^2}{l^2}\right)^{-1/4}, \quad (6.28)$$

which we can Taylor expand: at $x = 0$ we have

$$(1 - 12x)^{-1/4} = 1 - \frac{1}{4}(1 - 12 \times 0)^{-5/4}(-12x) + O(x^2) = 1 + 3x + O(x^2). \quad (6.29)$$

Therefore:

$$T = 2\pi \left(1 + 3 \left(\frac{GM}{l}\right)^2\right) + O\left(\left(\frac{GM}{l}\right)^4\right), \quad (6.30)$$

which is approximately 2π as we should expect: the Newtonian approximation is $l \gg GM$, and Newtonian orbits have a period of exactly 2π . Then we can read off the first-order correction directly from the first term in the expansion: it is

$$\delta\varphi = 6\pi \left(\frac{GM}{l}\right)^2. \quad (6.31)$$

The M here is the mass of the central object, while l is the angular momentum of the orbit.

Sheet 7

7.1 Photons travelling in the Schwarzschild metric

7.1.1 A different proof for the conservation of the component of the velocity of a geodesic along a Killing vector field

Here I present a different proof to what was done in the lectures for the fact that the component of the 4-velocity along the Killing vector field is conserved. This is not necessary to know for the exam, do skip this section if it does not interest you.

If the metric does not depend on the coordinate $\tilde{\alpha}$, then $\partial_{\tilde{\alpha}} g_{\mu\nu} = 0$. So, let us differentiate covariantly the vector $\xi_\mu = g_{\mu\nu} \delta_{\tilde{\alpha}}^\nu$. It will be apparent later that differentiating the lower-index vector field gives us the interesting property. We get

$$\nabla_\mu \xi_\nu = g_{\nu\sigma} \nabla_\mu \xi^\sigma = g_{\nu\sigma} \left(\partial_\mu \xi^\sigma + \Gamma_{\mu\rho}^\sigma \xi^\rho \right) = \Gamma_{\nu\mu\tilde{\alpha}}, \quad (7.1)$$

since the only component which survives the contraction with ξ is the one along $\tilde{\alpha}$; also, we lowered an index of the Christoffel symbols with the metric.

The explicit expression for the lower indices Christoffel symbols is

$$\Gamma_{\nu\mu\tilde{\alpha}} = \frac{1}{2} \left(g_{\mu\nu,\tilde{\alpha}} + g_{\mu\tilde{\alpha},\nu} - g_{\nu\tilde{\alpha},\mu} \right), \quad (7.2)$$

since by hypothesis any derivative of the metric along $\tilde{\alpha}$ is zero. So, we can directly see that the object $\nabla_\mu \xi_\nu$ is antisymmetric in its indices: this can be written as

$$\nabla_{(\mu} \xi_{\nu)} = 0, \quad (7.3)$$

and is called *Killing's equation*. We have shown that is equivalent to the metric not depending on the coordinate $x^{\tilde{\alpha}}$.

Now, we can quickly prove the conservation a component of the 4-velocity of a geodesic along the Killing vector field: we just need to differentiate $u^\mu \xi_\mu$ with respect to the arc parameter. Recall that geodesics are defined by the equation

$$a^\mu = \frac{d}{ds} u^\mu = u^\nu \nabla_\nu u^\mu = 0. \quad (7.4)$$

We find

$$u^\nu \nabla_\nu (u^\mu \xi_\mu) = u^\nu u^\mu \nabla_\nu \xi_\mu + \xi_\mu u^\nu \nabla_\nu u^\mu = 0, \quad (7.5)$$

where both terms are zero: the first because it is the contraction of an antisymmetric object with a symmetric one, and the second one because of the geodesic equation.

7.1.2 Conserved quantities in Schwarzschild motion

The Schwarzschild metric is given by

$$g_{\mu\nu} = \begin{bmatrix} -(1 - \frac{2GM}{r}) & 0 & 0 & 0 \\ 0 & (1 - \frac{2GM}{r})^{-1} & 0 & 0 \\ 0 & 0 & r^2 & 0 \\ 0 & 0 & 0 & r^2 \sin^2 \theta \end{bmatrix} \quad (7.6)$$

in the coordinates (t, r, θ, φ) . The vector fields $\xi_{(t)}^\mu = (1, \vec{0})$ and $\xi_{(\varphi)}^\mu = (0, 0, 0, 1)$ in these coordinates are Killing vector fields, since the metric does not depend on t or φ .

So, the following quantities are conserved in geodesic motion parametrized as $x^\mu(\lambda)$:⁴

$$e = -u^\mu g_{\mu\nu} \xi_{(t)}^\nu = -u^t g_{tt} \times 1 = \frac{dt}{d\lambda} \left(1 - \frac{2GM}{r}\right) \quad (7.7)$$

and

$$l = u^\mu g_{\mu\nu} \xi_{(\varphi)}^\nu = u^\varphi g_{\varphi\varphi} \times 1 = \frac{d\varphi}{d\lambda} r^2 \sin^2 \theta, \quad (7.8)$$

which for motion on the xy plane, for which $\theta = \pi/2$, reduces to $l = r^2 d\varphi/d\lambda$.

7.1.3 Photons escaping a black hole

The equation of motion can be derived from the normalization of the photon's four velocity: The equation $u^\mu u_\mu = 0$ can be written as

$$\left(\frac{dt}{d\lambda}\right)^2 g_{tt} + \left(\frac{dr}{d\lambda}\right)^2 g_{rr} + \left(\frac{d\theta}{d\lambda}\right)^2 g_{\theta\theta} + \left(\frac{d\varphi}{d\lambda}\right)^2 g_{\varphi\varphi} = 0, \quad (7.9)$$

but the term $d\theta/d\lambda$ is zero if we assume the motion to be in the xy plane, while the velocity components along t and φ can be written in terms of the integrals of motion: $dt/d\lambda = e(1 - 2GM/r)^{-1}$ and $d\varphi/d\lambda = l/r^2$. So, we find

$$-\left(1 - \frac{2GM}{r}\right)^{-2+1} e^2 + \left(1 - \frac{2GM}{r}\right)^{-1} \left(\frac{dr}{d\lambda}\right)^2 + l^2 r^{-4} r^2 = 0, \quad (7.10)$$

we divide through by $-g_{tt}$ and find:

$$-e^2 + \left(\frac{dr}{d\lambda}\right)^2 + \frac{l^2}{r^2} \left(1 - \frac{2GM}{r}\right) = 0, \quad (7.11)$$

or, dividing through by l :

$$-\frac{e^2}{l^2} + \frac{1}{l^2} \left(\frac{dr}{d\lambda}\right)^2 + \frac{1}{r^2} - \frac{2GM}{r^3} = 0. \quad (7.12)$$

We can give names to the terms in this equation: we call

$$V_{\text{eff}}(r) \equiv \frac{1}{r^2} - \frac{2GM}{r^3} \quad (7.13)$$

⁴There is a typo in the exercise sheet: a G is missing in the definition of e .

the *effective potential*, and

$$b^2 = \frac{l^2}{e^2} \quad (7.14)$$

the *impact parameter* (unjustified for now). Then, the equation is in the form

$$\frac{\dot{r}^2}{l^2} + V_{\text{eff}}(r) = \frac{1}{b^2}, \quad (7.15)$$

where we denoted derivation with respect to λ with a dot. So, we can study the motion of the photon as if it were 1-dimensional.

To study the problem, it is convenient to use the rescaled adimensional radial coordinate $R = r/2GM$. In this variable, the effective potential (which I will denote as just V hereafter) looks like:

$$V(R) = (2GM)^{-2} \left(R^{-2} - R^{-3} \right), \quad (7.16)$$

so we can readily differentiate it to find its stationary points: there is only one, the equation is $V'(R) \propto -2R^{-1} + 3R^{-2} = 0$, which is satisfied by $R = 3/2$.

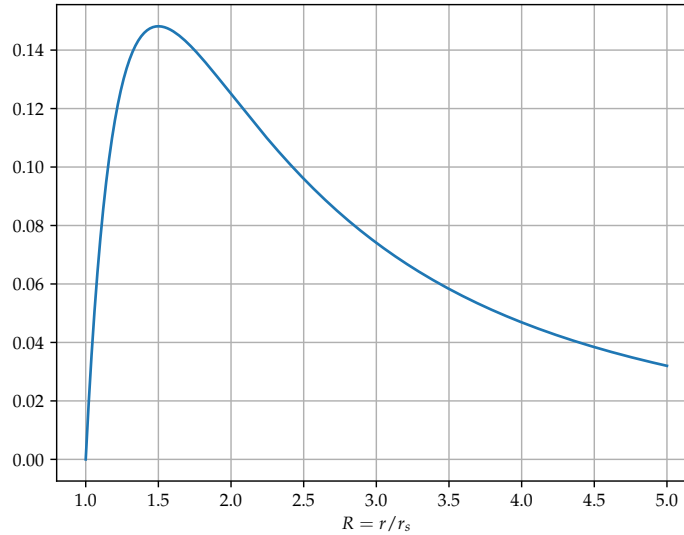


Figure 3: Plot of the function $R^{-2} - R^{-3}$.

The term b^{-2} is the maximum value which can be attained by the LHS: we can call it the total energy, the kinetic and potential contributions must add up to it. Also, the kinetic term is always positive. So, if the total energy is less than the

maximum of the potential, the photon is constrained to stay on either side of the potential barrier around $R = 3/2$. The potential there equals

$$V(3/2) = (2GM)^{-2} \left((3/2)^{-2} - (3/2)^{-3} \right) = \frac{4/27}{(2GM)^2} = \frac{1}{27(GM)^2}, \quad (7.17)$$

so the condition of the photon being above the potential barrier is

$$E_{\text{tot}} > V_{\text{max}} \quad (7.18)$$

$$\frac{e^2}{l^2} > \frac{1}{27G^2M^2} \quad (7.19)$$

$$\frac{l^2}{e^2} < 27G^2M^2, \quad (7.20)$$

and under this condition, if the photon initially has positive $dr/d\lambda$ it will remain as such, since everything is continuous and (if the strict inequality is satisfied) we can never have $dr/d\lambda = 0$.

If instead we had $l^2/e^2 < 27G^2M^2$ and the photon was initially travelling away from the black hole, there would come a point for which $dr/d\lambda$ would equal zero, and then it would become negative, since the photon could not go away from the center anymore.

This can be understood graphically by drawing horizontal lines of constant total energy in the potential diagram.

7.1.4 A basis for a stationary observer

If our observer's coordinates are $(t, r_*, \pi/2, \varphi_*)$, that is, it is at rest with respect to our spatial coordinates but it is not following geodesic motion, then it will have nonzero 4-acceleration. So, since we know that velocity and acceleration are orthogonal, we can form our coordinate system as $(u^\mu, a^\mu / \sqrt{a^\rho a_\rho}, e_\theta, e_\varphi)$, where the angular basis vectors are simply normalized vectors in the θ and φ directions.

This method has the advantage of being easily generalizable to find a comoving basis for any non-geodesic motion of our observer.

Their 4-velocity must be normalized so that $u^\mu u_\mu = -1$: so

$$u^\mu = \begin{bmatrix} \frac{dt}{d\tau} \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 1/\sqrt{1 - \frac{2GM}{r}} \\ 0 \\ 0 \\ 0 \end{bmatrix}, \quad (7.21)$$

then we can compute the 4-acceleration: it will be

$$a^\mu = u^\nu \nabla_\nu u^\mu = u^\nu \left(\partial_\nu u^\mu + \Gamma_{\nu\rho}^\mu u^\rho \right) \quad (7.22)$$

$$= \frac{1}{\sqrt{1 - \frac{2GM}{r}}} \left(\partial_t u^r + \Gamma_{tt}^r u^t \right) \quad (7.23)$$

$$= \frac{1}{\sqrt{1 - \frac{2GM}{r}}} \frac{1}{\sqrt{1 - \frac{2GM}{r}}} \frac{A'}{2B} \delta_r^\mu, \quad (7.24)$$

where $A = 1/B = (1 - 2GM/r)$ are the coefficients of the Schwarzschild metric, with respect to which the Christoffel symbols are expressed in (6.16). The δ_r^μ signifies that the only component which survives is the radial one. The two square root terms simplify the B , so we get that the only nonzero component of the 4-acceleration is:

$$a^r = \frac{A'}{2} = \frac{1}{2} \frac{d}{dr} \left(1 - \frac{2GM}{r} \right) = \frac{GM}{r^2}. \quad (7.25)$$

The actual value of this component is not actually useful to us — except as an illustration of the equivalence principle: it is the precise value of the Newtonian pseudo-force of acceleration — since we need a normalized basis. Therefore, we will use a vector parallel to a^μ but of length defined by the normalization $e_r \cdot e_r = 1$. So, we get for our basis:

$$\begin{cases} (e_t)^\mu = u^\mu = \left[(1 - 2GM/r)^{-1/2}, 0, 0, 0 \right]^\top \\ (e_r)^\mu = a^\mu / \sqrt{a_\rho a^\rho} = \left[0, (1 - 2GM/r)^{1/2}, 0, 0 \right]^\top \\ (e_\theta)^\mu = \left[0, 0, 1/r, 0 \right]^\top \\ (e_\varphi)^\mu = \left[0, 0, 0, 1/(r \sin \theta) \right]^\top \end{cases}, \quad (7.26)$$

where the last vector is written for a generic angle θ , but the sine is equal to one if $\theta = \pi/2$. This basis satisfies the property $e_\alpha \cdot e_\beta = \eta_{\alpha\beta}$.

We will denote vectors written with respect to this basis with a subscript c .

7.1.5 Critical angle of launch

In the flat frame, the 4-velocity of the photon launched at $\theta = \pi/2$ looks like:

$$u_{\text{ph}}^\mu = \begin{bmatrix} 1 \\ \cos \psi \\ 0 \\ \sin \psi \end{bmatrix}_c, \quad (7.27)$$

which means that in the Schwarzschild frame it looks like

$$u_{\text{ph}}^\mu = \begin{bmatrix} \frac{1}{\sqrt{1 - \frac{2GM}{r}}} \\ \cos \psi \sqrt{1 - \frac{2GM}{r}} \\ 0 \\ \frac{\sin \psi}{r} \end{bmatrix}. \quad (7.28)$$

This means that the parameter $l = r \sin \psi$, while $e = \sqrt{1 - 2GM/r}$.
The inequality to satisfy for the photon to be able to escape is:

$$\left[\frac{e^2}{l^2} \right]_{r_*} \geq \frac{1}{27G^2M^2}, \quad (7.29)$$

which translates to

$$\frac{1 - \frac{2GM}{r_*}}{r_*^2 \sin^2 \psi} \geq \frac{1}{27G^2M^2}, \quad (7.30)$$

or

$$r_*^2 \sin^2 \psi \leq 27G^2M^2(1 - 2GM/r_*), \quad (7.31)$$

which once again can be expressed in terms of the adimensional radial coordinate $R = r/2GM$: we find

$$\sin^2 \psi \leq \frac{27}{4R_*^2} \left(1 - \frac{1}{R_*} \right), \quad (7.32)$$

so the critical angle can be computed by making the relation explicitly in terms of ψ , which gives the plot shown in figure 4, for the equation

$$\psi = \arcsin \sqrt{\frac{27}{4R_*^2} \left(1 - \frac{1}{R_*} \right)}. \quad (7.33)$$

So, as we move closer to the horizon, the range of angles at which we can throw our photon and still have it escape decreases, until finally we can only throw it straight forward otherwise it will fall back in. After $r = 2GM$, not even that is enough.

All communication with the outside world is lost.

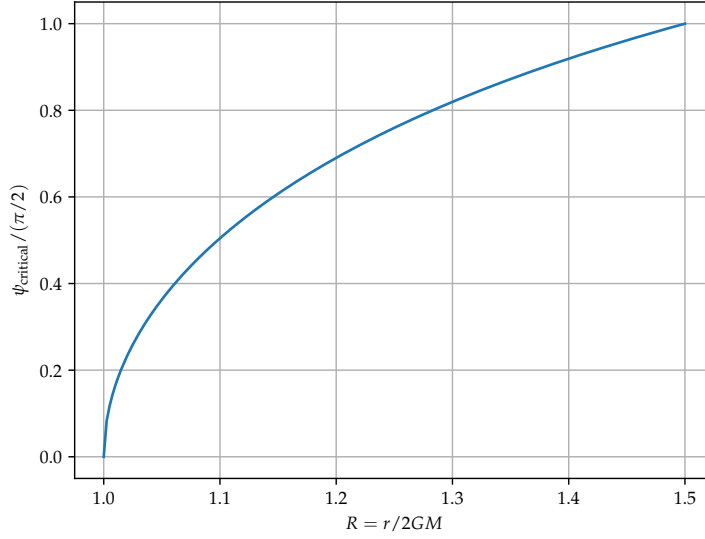


Figure 4: Critical angle ψ in terms of the adimensional radial coordinate $R = r/2GM$.

7.2 Light motion in a Schwarzschild geometry

This was done during the lectures, but I will recall it here.

We start from the equation of motion of a photon, a reframing of $u^2 = 0$:

$$\frac{1}{l^2} \left(\frac{dr}{d\lambda} \right)^2 + V_{\text{eff}}(r) = \frac{1}{b^2} = \frac{e^2}{l^2}. \quad (7.34)$$

We want to write this as a differential equation for the radius in terms of the angle φ : so, we use the expression of the first integral

$$l = \frac{d\varphi}{d\lambda} r^2 \implies \frac{d\varphi}{d\lambda} = \frac{l}{r^2} \implies \frac{d}{d\lambda} = \frac{l}{r^2} \frac{d}{d\varphi}. \quad (7.35)$$

So, we can rewrite

$$\left(\frac{dr}{d\lambda} \right)^2 = \frac{l^2}{r^4} \left(\frac{dr}{d\varphi} \right)^2, \quad (7.36)$$

which allows us to write the equation as

$$\frac{1}{r^4} \left(\frac{dr}{d\varphi} \right)^2 + V_{\text{eff}}(r) = \frac{1}{b^2}, \quad (7.37)$$

since the l^2 simplifies.

Now, notice that if we define $u = 1/r$ we find

$$\frac{du}{d\varphi} = -\frac{1}{r^2} \frac{dr}{d\varphi}, \quad (7.38)$$

which conveniently simplifies the r^{-4} : expressing everything with respect to u we get

$$\left(\frac{du}{d\varphi}\right)^2 + (u^2 - 2GMu^3) = \frac{1}{b^2}. \quad (7.39)$$

Now, we just need to differentiate everything to eliminate the constant term and find

$$2u'u'' + 2uu' - 6GMu^2u' = 0, \quad (7.40)$$

where we denoted derivatives with respect to φ with primes. One solution is $u' = 0$: a circular orbit, which we are not interested in now (and which is unstable...).

Otherwise, we can simplify a factor $2u'$: we find

$$u'' + u = 3GMu^2 \quad (7.41)$$

as we wanted to show.

7.2.1 Zero mass solution

If $M = 0$, our differential equation is simply $u'' + u = 0$, a harmonic oscillator. Our boundary condition is $r(\varphi = 0, \pi) \rightarrow \infty$, which means $u \rightarrow 0$ in those cases.

Also, one can geometrically see that $\sin \varphi = b/r$ where b is the impact parameter. Therefore, $bu = \sin \varphi$ or $u = \sin(\varphi)/b$. This actually is already a solution to our differential equation!

We are giving two boundary conditions, therefore the solution $u = \sin(\varphi)/b$ is unique.

7.2.2 Small mass deflection

We now insert a mass M , and consider a solution which is a perturbation to the sinusoidal one: our proposed solution is $u = \sin \varphi + w$, and we will only look at the first order in w . Substituting into $u'' + u = 3GMu^2$ we get

$$-\sin \varphi + w'' + \sin \varphi + w = 3GM \left(\sin^2 \varphi + \cancel{2w \sin \varphi} + w^2 \right), \quad (7.42)$$

where we kept only terms which are of first order in either GM or w , since both are small relative to the scale of the problem. So the differential equation for w is

$$w'' + w = 3GM \sin^2 \varphi. \quad (7.43)$$

This can be solved with an *ansatz* in the form $w = A + B \sin^2 \varphi$. Its derivatives are $w' = 2B \sin \varphi \cos \varphi = B \sin(2\varphi)$, and $w'' = 2B \cos(2\varphi) = B(1 - 2 \sin^2 \varphi)$.

Plugging this in we find

$$B(1 - 2 \sin^2 \varphi) + A + B \sin^2 \varphi = 3GM \sin^2 \varphi, \quad (7.44)$$

so equating the terms in $\sin^2 \varphi$ and the constant ones we get

$$\begin{cases} B + A = 0 \\ -B = 3GM \end{cases}, \quad (7.45)$$

so our solution is $w = 3GM(1 - \sin^2 \varphi)$.

7.3 Orbit at $7GM$

The radius of a $7GM_\odot$ orbit is equal to

$$7GM_\odot/c^2 \approx \quad (7.46)$$

$$7 \times 6.67 \times 10^{-11} \text{ kg m}^3 \text{ s}^{-2} \times 2 \times 10^{30} \text{ kg} \times (3 \times 10^8 \text{ ms}^{-1})^{-2} \approx \quad (7.47)$$

$$\approx 1.0 \times 10^4 \text{ m}, \quad (7.48)$$

or around 10 km.

The equation governing a circular orbit around a BH can be derived from the normalization of the 4-velocity $u \cdot u = -1$: in terms of $u = 1/r$ it is

$$u_c = \frac{GM}{l^2} + 3GM u_c^2, \quad (7.49)$$

and in our case we know that $u_c = 1/7GM$, substituting in we find

$$\frac{1}{7GM} = \frac{GM}{l^2} + \frac{3GM}{49(GM)^2}, \quad (7.50)$$

or

$$l^2 = (GM)^2 \left(\frac{1}{7} - \frac{3}{49} \right)^{-1} = 7(GM)^2 \left(1 - \frac{3}{7} \right)^{-1} = \frac{49}{4}(GM)^2, \quad (7.51)$$

so $l = 7GM/2$. Now, recall the definition of this first integral:

$$l = \frac{d\varphi}{d\tau} r^2, \quad (7.52)$$

into which we can substitute the expression we found:

$$\frac{7GM}{2} (7GM)^{-2} = \frac{1}{14GM} = \frac{d\varphi}{d\tau} = \omega_{\text{proper}}, \quad (7.53)$$

which gives us the angular velocity as measured by the orbiting observer. We actually have it in units of $1/\text{m}^3\text{s}^{-2}$, so we will need to multiply by c^3 to get inverse seconds.

This gives us a pulsation of

$$\omega_{\text{proper}} = \frac{c^3}{14GM_{\odot}} \approx 1.44 \times 10^5 \text{ rad/s}, \quad (7.54)$$

which corresponds to a period of

$$T_{\text{proper}} = \frac{2\pi}{\omega_{\text{proper}}} \approx 4.36 \times 10^{-4} \text{ s} = 436 \mu\text{s}. \quad (7.55)$$

Now, to compute the period for an observer at infinity: from the regular equation of motion of a massive observer we have

$$\frac{e^2 - 1}{2} = \frac{1}{2} \left(\frac{dr}{d\tau} \right)^2 + \underbrace{\left(-\frac{GM}{r} + \frac{l^2}{2r^2} - \frac{GMl^2}{r^3} \right)}_{V_{\text{eff}}}, \quad (7.56)$$

but since the orbit is circular r is constant, and we can substitute in our expressions for r and l to find out what e is: we get

$$\frac{e^2 - 1}{2} = -\frac{GM}{7GM} + \frac{(7GM/2)^2}{2 \times (7GM)^2} - \frac{GM(7GM/2)^2}{(7GM)^3} \quad (7.57)$$

$$= -\frac{1}{7} + \left(\frac{7}{2} \right)^2 \frac{1}{2 \times 7^2} - \left(\frac{7}{2} \right)^2 \frac{1}{7^3} \quad (7.58)$$

$$= -\frac{3}{56}, \quad (7.59)$$

therefore $e = 5\sqrt{7}/14$. Now recall the definition of e :

$$e = \frac{dt}{d\tau} \left(1 - \frac{2GM}{r} \right), \quad (7.60)$$

so

$$\frac{T_\infty}{T_{\text{proper}}} = \frac{dt}{d\tau} = \frac{5\sqrt{7}}{14} \left(1 - \frac{2GM}{7GM}\right)^{-1} = \frac{\sqrt{7}}{2} \approx 1.323, \quad (7.61)$$

therefore the period as measured by the outside observer is

$$T_\infty \approx 577 \mu\text{s}. \quad (7.62)$$

Do note that this is *not* the same as plainly applying the gravitational redshift formula as $T_1/T_2 = \sqrt{g_{tt}^1/g_{tt}^2}$: that gives a smaller ratio. The Doppler effects of the orbital speed do not average out over a period.

The orbit is a geodesic, so a pointlike observer feels no acceleration.

7.3.1 Tidal acceleration

A pointlike particle would feel no acceleration, however it would be quite uncomfortable to be in that orbit if one happens not to be pointlike. Let us compute the tidal effects on an extended observer.

They are described by the equation

$$\frac{d^2\zeta^\mu}{d\tau^2} = R^\mu_{\nu\rho\sigma} u^\nu u^\rho \zeta^\sigma, \quad (7.63)$$

where u^μ is the 4-velocity of a geodesic, ζ^μ is a small deviation in starting position for the geodesic such that the geodesic starting from there almost has the same tangent vector.

We can restrict ourselves to radial geodesic deviation: then we only need to compute the $R^\mu_{\nu\rho r}$ components of the Riemann tensor. I might do the full computation, but I found a source⁵ which gives the nonzero components:

$$R^r_{ttr} = (2GM(-2GM + r))/(r^4) \quad (7.64)$$

$$R^r_{\theta\theta r} = \frac{GM}{r} \quad (7.65)$$

$$R^r_{\varphi\varphi r} = \frac{GM \sin^2 \theta}{r}, \quad (7.66)$$

and since the orbital motion is assumed to happen on the $\theta = \pi/2$ plane, the

⁵<https://physics.stackexchange.com/questions/295814/non-zero-components-of-the-riemann-tensor-of-the-schwarzschild-metric>

formula simplifies to

$$\frac{d^2 \zeta^r}{d\tau^2} = R_{ttr}^r u^t u^t \zeta^r + R_{\varphi\varphi r}^r u^\varphi u^\varphi \zeta^r \quad (7.67)$$

$$= \left(\frac{e^2}{(1 - 2GM/r)^2} \frac{2GM}{r^3} \left(1 - \frac{2GM}{r} \right) + \frac{l^2}{r^4} \frac{GM}{r} \right) \zeta^r \quad (7.68)$$

$$= \left(\frac{e^2}{1 - 2GM/r} + \frac{l^2}{r^2} \right) \frac{2GM}{r^3} \zeta^r, \quad (7.69)$$

which holds in general: in our specific case, at $r = 7GM$ we find

$$\frac{d^2 \zeta^r}{d\tau^2} = \left(\frac{7}{5} \left(\frac{5\sqrt{7}}{14} \right)^2 + \left(\frac{7GM/2}{7GM} \right)^2 \right) \frac{2GM}{(7GM)^3} \zeta^r \quad (7.70)$$

$$= \frac{3}{343} \frac{1}{(GM)^2} \zeta^r, \quad (7.71)$$

so the object multiplying ζ^r , in units of inverse square seconds, is

$$\frac{3}{343} \frac{c^6}{(GM)^2} \approx 356 \times 10^6 \text{ s}^{-2} \approx (18.9 \text{ kHz})^2. \quad (7.72)$$

The acceleration which would be experienced from one side of the other of a meter-long observer would then be of around 36 Mg.

7.3.2 A proof for the geodesic deviation formula

The starting separation between geodesics is not, properly speaking, a *vector* since it does not belong to the tangent space, however we can be sloppy and approximate it as a tangent vector. So, we take it to be a basis vector $\zeta^\mu = (e_{\tilde{\alpha}})^\mu$: then it is a fact from differential geometry that under our assumptions

$$\zeta^\mu \nabla_\mu u^\nu = u^\mu \nabla_\mu \zeta^\nu, \quad (7.73)$$