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# Cosmology — Term 4 Exam — Solution

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## 1. John Tries to Graffiti Mary's Ship

(a) Length contraction by  $\gamma \equiv \frac{1}{\sqrt{1-v_{\text{rel}}^2}}$  says that Mary's ship is shortened by a factor of  $\gamma$ . Therefore,

$$\text{MF} = \left(0, \frac{L}{2\gamma}\right)$$

$$\text{MB} = \left(0, -\frac{L}{2\gamma}\right)$$

(b) Plugging in the coordinates of GF, which are  $t = 0$  and  $x = \frac{L}{2}$ , into

The  $y$  and  $z$  components are respectively equal in both frames, as before. Then the inverse Lorentz transformation equations become

$$\begin{aligned} t' &= -v_{\text{rel}}\gamma x + \gamma t \\ x' &= \gamma x - v_{\text{rel}}\gamma t \\ y' &= y \\ z' &= z \end{aligned} \quad (\text{L-11a})$$

we find

$$\text{GF} = \left(-v_{\text{rel}}\gamma \frac{L}{2}, \gamma \frac{L}{2}\right)$$

in Mary's coordinates.

(c) And we find

$$\text{GB} = \left(v_{\text{rel}}\gamma \frac{L}{2}, -\gamma \frac{L}{2}\right)$$

in Mary's coordinates.

(d) (i) Mary forgot about the Relativity of Simultaneity. (ii) The paint bomb ahead of her ship went off  $\gamma \frac{L}{2}$  too early, and the paint bomb at the back of her ship went off  $\gamma \frac{L}{2}$  too late.

(e)  $\frac{L}{2} = 20 \text{ m}$ ,  $v_{\text{rel}} = \frac{3}{5}$ ,  $\gamma = \frac{5}{4}$ , so  $\text{MF} = \left(0, \frac{L}{2\gamma}\right) = \left(0, 20 \text{ m} \cdot \frac{4}{5}\right) = (0, 16 \text{ m})$  and  $\text{MB} = (0, -16 \text{ m})$ , which is well within the ends of his lab.

(f)  $\text{GF} = (-15 \text{ m}, 25 \text{ m})$  and  $\text{GB} = (15 \text{ m}, -25 \text{ m})$  in Mary's coordinates.

## Problem 2 — The Famous Equation, $E = mc^2$

(a) Because wristwatch time and coordinate time are the same for a particle at rest in a coordinate system, in that system  $E = m \frac{\Delta t}{\Delta \tau} = m$ .

(b)  $\Delta x = v \Delta t$

(c)  $\Delta \tau = \sqrt{(\Delta t)^2 - (\Delta x)^2}$ .

(d)  $\Delta \tau = \sqrt{(\Delta t)^2 - (\Delta x)^2} = \sqrt{(\Delta t)^2 - (v \Delta t)^2} = \sqrt{1 - v^2} \Delta t = \Delta t / \gamma$ . So,  $m \frac{\Delta t}{\Delta \tau} = m \gamma$ .

(e)  $\frac{\Delta t}{\Delta \tau} = \gamma$

(f)  $p = m \frac{\Delta x}{\Delta \tau} = m \frac{\Delta t}{\Delta \tau} \frac{\Delta x}{\Delta t} = m \gamma \frac{\Delta x}{\Delta t} = m \gamma v$ .

(g)  $E = m \gamma = m \frac{1}{\sqrt{1-0.995^2}} = m \frac{1}{\sqrt{1-0.99}} m \frac{1}{\sqrt{0.01}} = 10 m$

(h)  $E = m \gamma = m \frac{1}{\sqrt{1-0.99995^2}} = m \frac{1}{\sqrt{1-0.9999}} m \frac{1}{\sqrt{0.0001}} = 100 m$

## Problem 3 — Inward-Going Photons on the $[t, r]$ -Slice Outside the Event Horizon

We start with the metric in Eq. (5) of TWB Chapter 3:  $(\Delta \tau)^2 = (1 - 2M/r) (\Delta t)^2 - \frac{(\Delta r)^2}{1-2M/r} - r^2 (\Delta \phi)^2$ .

(a)  $(\Delta \tau)^2 = (1 - 2M/r) (\Delta t)^2 - \frac{(\Delta r)^2}{1-2M/r}$ .

(b)  $0 = (1 - 2M/r) (\Delta t)^2 - \frac{(\Delta r)^2}{1-2M/r}$  or  $(1 - 2M/r) (\Delta t)^2 = \frac{(\Delta r)^2}{1-2M/r}$  or  $(\Delta t)^2 = \frac{(\Delta r)^2}{(1-2M/r)^2}$ .

So,  $|\Delta t| = \frac{|\Delta r|}{1-2M/r}$ .

(c)  $\Delta t = \frac{-\Delta r}{1-2M/r}$

(d)  $\Delta y = \frac{-\Delta x}{1-2/x}$

(e) We will start at  $x = 4.0$  and finish at  $x = 2.4$  and do that in 8 steps of  $\Delta x = -0.2$  each. Fill in the final two columns of the table below using the formula you found in (d).

```

In[ ]:= table2 = Table[
  {i, 4.0 - 0.2 i, "-0.2",
   If[True, "", Round[0.2 / (1 - 2 / (4.0 - 0.2 i)), 0.01]]}, {i, 0, 7, 1}];
table2WithHeader =
  PrependTo[table2, {"i", "xi", "Δx", "Δyi", "Cumulative change in y"}];
TableForm[table2WithHeader]

```

Out[ ]:= TableForm=

i	x <sub>i</sub>	Δx	Δy <sub>i</sub>	Cumulative change in y
0	4.	-0.2	0.40	0.40
1	3.8	-0.2	0.42	0.82
2	3.6	-0.2	0.45	1.27
3	3.4	-0.2	0.49	1.76
4	3.2	-0.2	0.53	2.29
5	3.	-0.2	0.60	2.89
6	2.8	-0.2	0.70	3.59
7	2.6	-0.2	0.87	4.46

In the spirit of continuing to not need a calculator, below is a table of miscellaneous combinations, some of which are relevant.

```

In[ ]:= TableForm[
  PrependTo[Table[{Round[x, 0.1], Round[0.2 / x, 0.01], Round[0.2 / (1 - 2 / x), 0.01],
    Round[0.2 / Sqrt[1 - 2 / x], 0.01]}, {x, 4.0, 2.6, -0.2}],
  {"xi", "0.2/xi", "0.2/(1-2/xi)", "0.2/sqrt(1-2/xi)"}]]

```

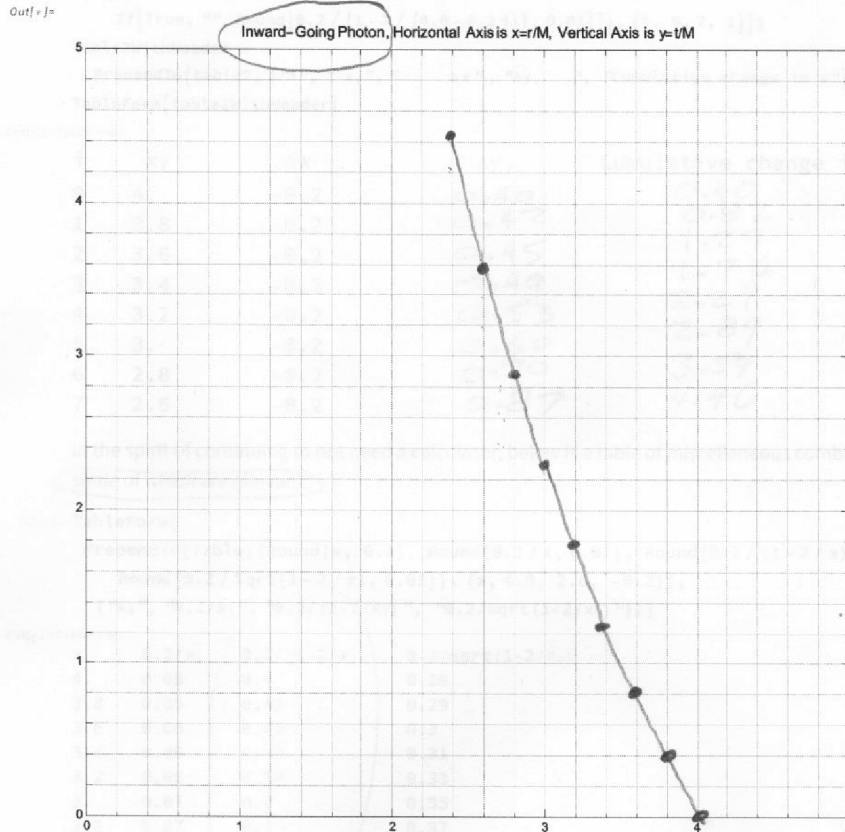
Out[ ]:= TableForm=

x <sub>i</sub>	0.2/x <sub>i</sub>	0.2/(1-2/x <sub>i</sub> )	0.2/sqrt(1-2/x <sub>i</sub> )
4.	0.05	0.4	0.28
3.8	0.05	0.42	0.29
3.6	0.06	0.45	0.3
3.4	0.06	0.49	0.31
3.2	0.06	0.53	0.33
3.	0.07	0.6	0.35
2.8	0.07	0.7	0.37
2.6	0.08	0.87	0.42

This is the only column that is relevant.

(g) Graph  $y$  vs.  $x$  starting with  $x = 4.0$ ,  $y = 0.0$ , and working your way inward. The last row of the table is the row that goes from  $x = 2.6$  to  $x = 2.4$ .

```
In[ ]:= Plot[{}, {x, 0, 5}, PlotRange -> {{0, 5}, {0, 5}}, AspectRatio -> 1, GridLines -> {Range[0, 5, 0.2], Range[0, 5, 0.2]},  
Frame -> True, PlotLabel -> "Inward-Going Photon, Horizontal Axis is x=r/M, Vertical Axis is y=t/M"]
```



This is a numerical solution to a graph that you made on Problem Set 5 (see Problem 3(d)).

## 4. Hanging Out Near Gargantuan

(Gargantuan is the black hole in *Interstellar*.)

(a) Again, we start with the metric in Eq. (5) of TWB Chapter 3,

$$(\Delta\tau)^2 = (1 - 2M/r)(\Delta t)^2 - \frac{(\Delta r)^2}{1 - 2M/r} - r^2(\Delta\phi)^2, \text{ and put in } \Delta r = \Delta\phi = 0 \text{ to get:}$$

$$(\Delta\tau)^2 = (1 - 2M/r)(\Delta t)^2$$

(b) Take the square root and make the assumptions suggested:

$$\Delta\tau = \sqrt{1 - 2M/r} \Delta t$$

(c) For the clocks at either of the two positions, we use the Part (b) equation:

$$T = \Delta\tau_L = \sqrt{1 - 2M/r_L} \Delta t_L \text{ or } \Delta t_L = T / \sqrt{1 - 2M/r_L}.$$

$$T = \Delta\tau_H = \sqrt{1 - 2M/r_H} \Delta t_H \text{ or } \Delta t_H = T / \sqrt{1 - 2M/r_H}.$$

(d) With  $r_H = \infty$ ,  $\Delta t_H = T$ , and  $\Delta t_L = T / \sqrt{1 - 2M/r_L}$  is larger than  $\Delta t_H$ , because it has a number less than 1 in the square root of the denominator.

(e) Per part (d), for a given amount of coordinate time, the person at  $r_L$  is aging less. Put in  $r_L = \frac{200M}{99}$ .

$$\Delta t_L = T / \sqrt{1 - 2M/(200M/99)} = T / \sqrt{1 - 99/100} = T / \sqrt{0.01} = T/0.1 = 10 T.$$

If a person hangs out for 7 years of wristwatch time at  $r_L$ , 70 years of coordinate time and proper time will have elapsed for the person at  $r_H = \infty$ !