Physics 14-01 Einstein's Postulates and Time Dilation **Name: _______________**

Event

- Physical _______________ in a certain _______________ at a certain _______________.

Reference Frame

- Coordinate _______________ (x, y, z) and _______________

Inertial Reference Frame

- Reference frame where _______________ Law of _______________ is _______________
- No _______________
- No _______________

Einstein's Postulates

The Relativity Postulate

- The laws of _______________ are the _______________ in _______________ inertial reference frame.

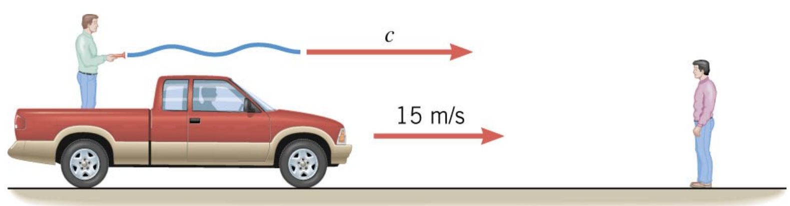
The Speed of Light Postulate

- The speed of light in a _______________, measured in __________ inertial reference frame, ___________ has the ___________ value of c, no matter how fast the _______________ of light and the _______________ are moving ____________ to each other.

Consequences of Relativity Postulate

- _______________ inertial reference frame is as _______________ as any other.
- You _______________ say any reference frame is _______________ at _______________.
- There is no _______________ velocity or rest, only velocity _______________ to the _______________ frame.

Explanation of Speed of Light Postulate

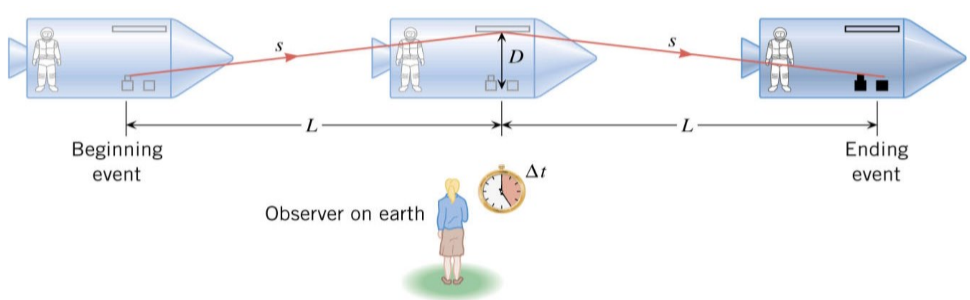


- The observer on the truck _______________ speed of _______________ to be _______________ since he is _______________ the light.
- Logic says the observer on the _______________ measures the speed of _______________ to be _______________, but he doesn't.
- The observer on the _______________ measures speed of light to be _______________ also.
- Verified by _________________ many times.

Simultaneous

- Just because two events _______________ simultaneous to _______________ observer does not mean _______________ observes see the _______________ simultaneously

Time Dilation



- Astronaut measures _________ by aiming a ____________ at a mirror. The light ___________ from the mirror and hits a _______________.
- The person on _______________ says that the time of the event must be _____________ because she sees the laser beam go _____________.

$$\Delta t = \frac{\Delta t_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

- Where Δt_0 = proper time measured in a reference frame at rest relative to the event, Δt = dilated time measured in a reference frame moving relative to the event, v = relative speed between the observers, c = speed of light in a vacuum

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Physics 14-01 Einstein's Postulates and Time Dilation **Name: ______________**

Let's say the USS Enterprise's 1/3 impulse speed is one-quarter the speed of light. If Spock, in the ship, says the planet will blow up in 10 minutes, how long does the away team have to beam up?

Picard is on Rigel 7 and needs to go to Earth 776.6 light-years away, but the Enterprise's warp drive is broken. If full impulse is ¾ the speed of light, how long will a Rigelian think it will take the Enterprise to get to Earth?

How long will the Enterprise's crew think it will take?

Practice Work

1. Which of Einstein's postulates of special relativity includes a concept that does not fit with the ideas of classical physics? Explain.
2. Is Earth an inertial frame of reference? Is the Sun? Justify your response.
3. When you are flying in a commercial jet, it may appear to you that the airplane is stationary and the Earth is moving beneath you. Is this point of view valid? Discuss briefly.
4. Does motion affect the rate of a clock as measured by an observer moving with it? Does motion affect how an observer moving relative to a clock measures its rate?
5. To whom does the elapsed time for a process seem to be longer, an observer moving relative to the process or an observer moving with the process? Which observer measures proper time?
6. (a) What is γ if v = 0.100c? (b) If v = 0.900c? (OpenStax 28.2) **1.00504, 2.29**
7. Particles called π-mesons are produced by accelerator beams. If these particles travel at 2.70×10^{8} m/s and live 2.60×10^{-8} s when at rest relative to an observer, how long do they live as viewed in the laboratory? (OpenStax 28.3) $\mathbf{5.96 \times 10^{-8}\ s}$
8. Suppose a particle called a kaon is created by cosmic radiation striking the atmosphere. It moves by you at 0.980c, and it lives 1.24×10^{-8} s when at rest relative to an observer. How long does it live as you observe it? (OpenStax 28.4) $\mathbf{6.23 \times 10^{-8}\ s}$
9. A neutral π-meson is a particle that can be created by accelerator beams. If one such particle lives 1.40×10^{-16} s as measured in the laboratory, and 0.840×10^{-16} s when at rest relative to an observer, what is its velocity relative to the laboratory? (OpenStax 28.5) **0.800c**
10. If relativistic effects are to be less than 1%, then γ must be less than 1.01. At what relative velocity is γ = 1.01? (OpenStax 28.7) **0.140c**
11. (a) At what relative velocity is γ = 1.50? (b) At what relative velocity is γ = 100? (OpenStax 28.9) **0.745c, 0.99995c**

Physics 14-02 Length Contraction | *Name: _______________*

Length Contraction

- Since the _____________ moving _____________ the event measures a different _____________ than the observer _____________ moving with the event, are the _____________ different?
  - $x = vt$
  - Both _____________ agree on _____________
  - t is different by $\frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$
  - So x must be different by $\frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$ also
- The _____________ measured by a person at _____________ with the event is _____________ than that measured by person at _____________ with respect to the _____________.

$$L = L_0\sqrt{1-\frac{v^2}{c^2}} = \frac{L_0}{\gamma}$$

  - Where L_0 = proper length (Length between 2 points as measured by person at rest with the points.)
- Length only contracts along the direction of _____________, the others _____________ the _____________

When the Starship Enterprise travels at impulse (v = 0.7c), a ground based observer measures the ship as 707 ft long. How long does the crew measure the ship?

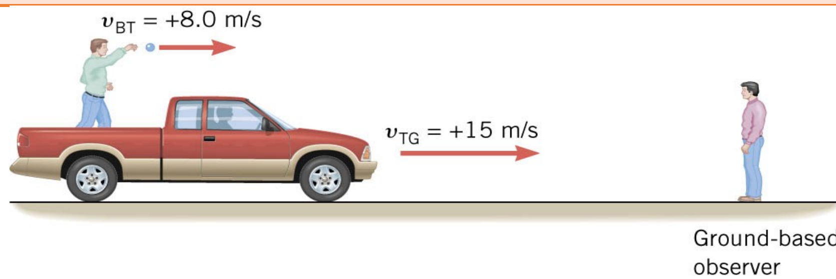
Practice Work

1. To whom does an object seem greater in length, an observer moving with the object or an observer moving relative to the object? Which observer measures the object's proper length?
2. Relativistic effects such as time dilation and length contraction are present for cars and airplanes. Why do these effects seem strange to us?
3. Suppose an astronaut is moving relative to the Earth at a significant fraction of the speed of light. (a) Does he observe the rate of his clocks to have slowed? (b) What change in the rate of Earth-bound clocks does he see? (c) Does his ship seem to him to shorten? (d) What about the distance between stars that lie on lines parallel to his motion? (e) Do he and an Earth-bound observer agree on his velocity relative to the Earth?
4. A spaceship, 200 m long as seen on board, moves by the Earth at 0.970c. What is its length as measured by an Earth-bound observer? (OpenStax 28.12) **48.6 m**
5. How fast would a 6.0 m-long sports car have to be going past you in order for it to appear only 5.5 m long? (OpenStax 28.13) **0.400c**
6. (a) How long does it take the astronaut in to travel 4.30 ly at 0.99944c (as measured by the Earthbound observer)? (b) How long does it take according to the astronaut? (c) Verify that these two times are related through time dilation with γ=30.00 as given. (OpenStax 28.16) **4.303 y, 0.1434 y, 30.0**
7. (a) How fast would an athlete need to be running for a 100-m race to look 100 yd long? (b) Is the answer consistent with the fact that relativistic effects are difficult to observe in ordinary circumstances? Explain. (OpenStax 28.17) **0.405c, yes**
8. (a) Find the value of γ for the following situation. An astronaut measures the length of her spaceship to be 25.0 m, while an Earth-bound observer measures it to be 100 m. (b) What is unreasonable about this result? (c) Which assumptions are unreasonable or inconsistent? (OpenStax 28.18) **0.250, γ must be ≥ 1, The earthbound observer must measure a shorter length, so it is unreasonable to assume a longer length.**

Physics 14-03 Relativistic Addition of Velocities Name: _______________

Relativistic Addition of Velocities

Classical physics



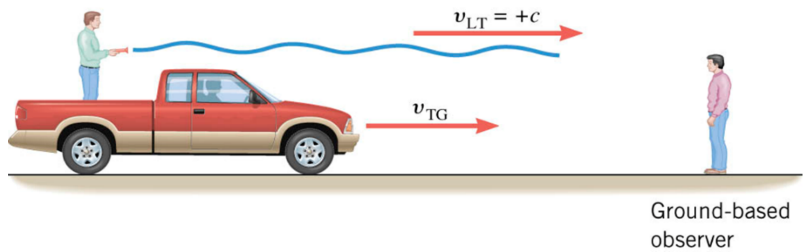
$$v_{BT} + v_{TG} = v_{BG}$$
$$v_{BT} = -v_{TB}$$

What if the combination of the ___________ and the ______ added to be more than the speed of _______?

- The _____________-based observer would observe the ball to travel _____________ than light.
- This _____________ happen.

Relativistic Addition of Velocity

$$v_{LG} = \frac{v_{LT} + v_{TG}}{1 + \frac{v_{LT} v_{TG}}{c^2}}$$



At what speed does the ground-based observer see the light travel?

Doppler shift for relative velocity

$$\lambda_{obs} = \lambda_s \sqrt{\frac{1 + \frac{u}{c}}{1 - \frac{u}{c}}}$$

- u is relative _____________ of _____________ to _____________
  - Positive if moving _____________

$$f_{obs} = f_s \sqrt{\frac{1 - \frac{u}{c}}{1 + \frac{u}{c}}}$$

The starship Enterprise moves at 0.9c relative to the earth and a Klingon Bird-of-Prey moves the same direction at 0.7c relative to the earth. What does the navigator of the Bird-of-Prey report for the speed of the Enterprise?

If the Enterprise has blue (λ = 475 nm) lights, what wavelength does the Klingon ship see as it leaves?

Physics 14-03 Relativistic Addition of Velocities	*Name: _______________*
Practice Work	

1. Explain the meaning of the terms "red shift" and "blue shift" as they relate to the relativistic Doppler effect.
2. What happens to the relativistic Doppler effect when relative velocity is zero? Is this the expected result?
3. Is the relativistic Doppler effect consistent with the classical Doppler effect in the respect that λ_{obs} is larger for motion away?
4. Suppose a spaceship heading straight towards the Earth at 0.750c can shoot a canister at 0.500c relative to the ship. (a) What is the velocity of the canister relative to the Earth, if it is shot directly at the Earth? (b) If it is shot directly away from the Earth? (OpenStax 28.20) **0.909c, 0.400c**
5. Repeat the previous problem with the ship heading directly away from the Earth. (OpenStax 28.21) **-0.400c, -0.909c**
6. If a spaceship is approaching the Earth at 0.100c and a message capsule is sent toward it at 0.100c relative to the Earth, what is the speed of the capsule relative to the ship? (OpenStax 28.22) **0.198c**
7. If a galaxy moving away from the Earth has a speed of 1000 km/s and emits 656 nm light characteristic of hydrogen (the most common element in the universe). (a) What wavelength would we observe on the Earth? (b) What type of electromagnetic radiation is this? (c) Why is the speed of the Earth in its orbit negligible here? (OpenStax 28.24) **658 nm, red, it's v << c**
8. A space probe speeding towards the nearest star moves at 0.250c and sends radio information at a broadcast frequency of 1.00 GHz. What frequency is received on the Earth? (OpenStax 28.25) **775 MHz**
9. If two spaceships are heading directly towards each other at 0.800c, at what speed must a canister be shot from the first ship to approach the other at 0.999c as seen by the second ship? (OpenStax 28.26) **0.991c**
10. When a missile is shot from one spaceship towards another, it leaves the first at 0.950c and approaches the other at 0.750c . What is the relative velocity of the two ships? (OpenStax 28.28) **-0.696c away**
11. Near the center of our galaxy, hydrogen gas is moving directly away from us in its orbit about a black hole. We receive 1900 nm electromagnetic radiation and know that it was 1875 nm when emitted by the hydrogen gas. What is the speed of the gas? (OpenStax 28.30) **0.01324c**

Physics 14-04 Relativistic Momentum — *Name:* ______________

Law of Conservation of Momentum

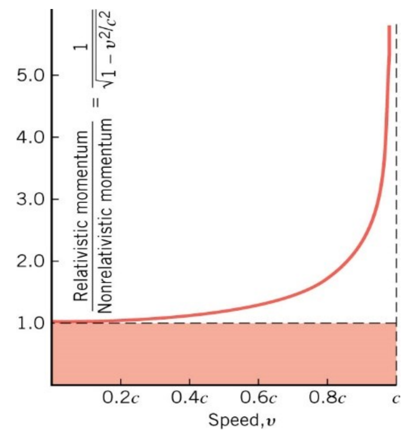
- The __________ momentum of a closed __________ does not __________.

$$p = mv$$

- However, when __________ approaches __________, we must adjust the __________

$$p = \frac{mv}{\sqrt{1 - \frac{v^2}{c^2}}}$$

- ____________ momentum is always __________ than ________________ momentum because
- $\sqrt{1 - \frac{v^2}{c^2}} < 1$
- Since we __________ by the radical in the formula, the result is a __________ number.
- Notice that when the __________ is near 0, the ____________ momentum is near the ________________.
- When the speed is near c, the ____________ momentum increases ________________.



In a game of Dom'Jot, a small ball (0.5 kg) is hit across a table. If the ball moves at 3 m/s and the speed of light in a vacuum is 4 m/s, what is the relativistic momentum of the ball?

The nonrelativistic momentum?

Practice Work

1. Find the momentum of a helium nucleus having a mass of 6.68×10^{-27} kg that is moving at 0.200c. (OpenStax 28.35) $\mathbf{4.09 \times 10^{-19}}$ **kg m/s**
2. What is the momentum of an electron traveling at 0.980c? (OpenStax 28.36) $\mathbf{1.35 \times 10^{-21}}$ **kg m/s**
3. What is the velocity of an electron that has a momentum of 3.04×10^{-21} kg·m/s? Note that you must calculate the velocity to at least four digits to see the difference from c. (OpenStax 28.39) $\mathbf{2.988 \times 10^{8}}$ **m/s**
4. Find the velocity of a proton that has a momentum of 4.48×10^{-19} kg·m/s. (OpenStax 28.40) $\mathbf{2.00 \times 10^{8}}$ **m/s**
5. (a) Calculate the speed of a 1.00-μg particle of dust that has the same momentum as a proton moving at 0.999c. (b) What does the small speed tell us about the mass of a proton compared to even a tiny amount of macroscopic matter? (OpenStax 28.41) $\mathbf{1.12 \times 10^{-8}}$ **m/s, mass of proton is tiny**

Physics 14-05 Relativistic Energy **Name: _______________**

The ____________ energy of an ____________

$$E = \frac{mc^2}{\sqrt{1-\frac{v^2}{c^2}}}$$

If the object is ____________ moving, the ____________ energy is

$$E_0 = mc^2$$

How much energy is in a 5-gram pen at rest?

How long will that run a 60-W light bulb?

If the object is ____________, then the total ____________ is $E = E_0 + KE$

$$KE = mc^2\left(\frac{1}{\sqrt{1-\frac{v^2}{c^2}}} - 1\right)$$

____________ and ____________ are the ____________

- A change in ____________, means a change in the ____________.
- For example, you pick up your backpack and increase its __________________ ______________ energy.
  - Since the ____________ increases, the mass must ____________.
  - So when you ____________ your backpack, it is actually ____________ than when it is on the ____________.

The sun radiates electromagnetic energy at 3.92×10^{26} W. How much mass does the sun lose in 1 year?

A ____________ consequence

- Objects with ____________ cannot reach the ____________ of ____________.
- This is because it would take an ____________ amount of ____________.

Physics 14-05 Relativistic Energy	***Name: _______________***
Practice Work	

1. How are the classical laws of conservation of energy and conservation of mass modified by modern relativity?
2. Consider a thought experiment. You place an expanded balloon of air on weighing scales outside in the early morning. The balloon stays on the scales and you are able to measure changes in its mass. Does the mass of the balloon change as the day progresses? Discuss the difficulties in carrying out this experiment.
3. Given the fact that light travels at *c*, can it have mass? Explain.
4. What is the rest energy of an electron, given its mass is 9.11×10^{-31} kg? Give your answer in joules and MeV. (OpenStax 28.43) **0.512 MeV**
5. Find the rest energy in joules and MeV of a proton, given its mass is 1.67×10^{-27} kg. (OpenStax 28.44) $\mathbf{1.503 \times 10^{-10}}$ **J, 939 MeV**
6. A supernova explosion of a 2.00×10^{31} kg star produces 1.00×10^{44} J of energy. (a) How many kilograms of mass are converted to energy in the explosion? (b) What is the ratio $\frac{\Delta m}{m}$ of mass destroyed to the original mass of the star? (OpenStax 28.47) $\mathbf{1.11 \times 10^{27}}$ **kg,** $\mathbf{5.556 \times 10^{-5}}$
7. There is approximately 10^{34} J of energy available from fusion of hydrogen in the world's oceans. (a) If 10^{33} J of this energy were utilized, what would be the decrease in mass of the oceans? (b) How great a volume of water does this correspond to? (c) Comment on whether this is a significant fraction of the total mass of the oceans. (OpenStax 28.50) $\mathbf{1 \times 10^{16}}$ **kg,** $\mathbf{1 \times 10^{13}}$ $\mathbf{m^3}$**, no**
8. A muon has a rest mass energy of 105.7 MeV, and it decays into an electron and a massless particle. (a) If all the lost mass is converted into the electron's kinetic energy, find γ for the electron. (b) What is the electron's velocity? (OpenStax 28.51) **208, 0.999988c**
9. Alpha decay is nuclear decay in which a helium nucleus is emitted. If the helium nucleus has a mass of 6.80×10^{-27} kg and is given 5.00 MeV of kinetic energy, what is its velocity? (OpenStax 28.54) **0.0511c**
10. (a) Beta decay is nuclear decay in which an electron is emitted. If the electron is given 0.750 MeV of kinetic energy, what is its velocity? (b) Comment on how the high velocity is consistent with the kinetic energy as it compares to the rest mass energy of the electron. (OpenStax 28.55) **0.914c**
11. A positron is an antimatter version of the electron, having exactly the same mass. When a positron and an electron meet, they annihilate, converting all of their mass into energy. (a) Find the energy released, assuming negligible kinetic energy before the annihilation. (b) If this energy is given to a proton in the form of kinetic energy, what is its velocity? (c) If this energy is given to another electron in the form of kinetic energy, what is its velocity? (OpenStax 28.56) $\mathbf{1.64 \times 10^{-13}}$ **J, 0.0467c, 0.943c**

Physics Unit 14: Special Relativity Review **Name: _______________**

1. Define inertial reference frame, proper time, dilated time, proper length, contracted length, relativistic momentum, nonrelativistic momentum,
2. Know the relativity postulates and their consequences.
3. An astronaut travels at 1×10^8 m/s for 24 hours as measured by ground control. What is the time as measured by the astronaut?
4. An alien flies by a football game at 0.90c and measures the time it takes to kick a field goal as 0.50 s. What is the proper time for the kick?
5. A meter stick is measured to be 50 cm long. How fast must the meter stick be traveling?
6. What is the relativistic momentum of an electron traveling at 0.99c?
7. A car is 500 kg at rest. What is the increase in its energy when it is traveling at 0.90c?
8. How much energy will be released when 2 kg of pencil is converted to energy?
9. What is the ratio of relativistic kinetic energy to classical kinetic energy for a 500 kg car traveling at 0.90c?
10. The *Enterprise* moves at 0.9c relative to earth and the Klingon Bird-of-Prey moves at 0.7c relative to earth. What does the navigator of the Bird-of-Prey report for the speed of the *Enterprise*?
11. The Klingon Battle Cruiser moving at 0.7c relative to earth fires a torpedo at 0.5c relative to the Battle Cruiser. What is the speed of the torpedo as observed from earth?
12. The Klingon Battle Cruise approaches earth at 0.7c relative to earth. It passes the Ferengi Shuttle at 0.5c relative to the shuttle. What is the speed of the Shuttle relative to the earth?
13. The starship *Enterprise* approaches the planet Risa at a speed of 0.5c relative to the planet. On the way, it overtakes the intergalactic freighter *Astra*. The relative speed of the two ships as measured by the navigator on the *Enterprise* is 0.1c. If the *Astra* has a red (λ = 650 nm) navigation light, what wavelength will the *Enterprise* see as they approach the *Astra*.

3. $\Delta t = 24\ h, v = 1 \times 10^8 \frac{m}{s},\ \Delta t_0 = ?$

$$\Delta t = \frac{\Delta t_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$24\ h = \frac{\Delta t_0}{\sqrt{1 - \frac{\left(1 \times 10^8 \frac{m}{s}\right)^2}{\left(3 \times 10^8 \frac{m}{s}\right)^2}}}$$

$$24\ h = \frac{\Delta t_0}{\sqrt{1 - \frac{1}{9}}}$$

$$24\ h \sqrt{\frac{8}{9}} = \Delta t_0$$

$$\boldsymbol{\Delta t_0 = 22.6\ h}$$

4. $v = 0.90c, \Delta t = 0.50\ s, \Delta t_0 = ?$

$$0.50\ s = \frac{\Delta t_0}{\sqrt{1 - \frac{(0.90c)^2}{c^2}}}$$

$$0.50\ s\sqrt{1 - 0.90^2} = \Delta t_0$$

$$\boldsymbol{\Delta t_0 = 0.218\ s}$$

5. $L_0 = 1\ m, L = 0.5\ m, v = ?$

$$L = L_0\sqrt{1 - \frac{v^2}{c^2}}$$

$$0.5\ m = 1\ m\sqrt{1 - \frac{v^2}{c^2}}$$

$$0.25 = 1 - \frac{v^2}{c^2}$$

$$0.75 = \frac{v^2}{c^2}$$

$$v = \sqrt{0.75}c$$

$$\boldsymbol{v = 0.87c}$$

6. $v = 0.99c, m = 9.11 \times 10^{-31}\ kg, p = ?$

$$p = \frac{mv}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$p = \frac{(9.11 \times 10^{-31}\ kg)\left(0.99\left(3 \times 10^8 \frac{m}{s}\right)\right)}{\sqrt{1 - \frac{(0.99c)^2}{c^2}}}$$

$$\boldsymbol{p = 1.92 \times 10^{-21}\ kg\ m/s}$$

7. $m = 500\ kg, v = 0.90c, KE = ?$

$$KE = mc^2\left(\frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} - 1\right)$$

$$KE = (500\ kg)(c^2)\left(\frac{1}{\sqrt{1 - \frac{0.90c^2}{c^2}}} - 1\right)$$

$$\boldsymbol{KE = 5.82 \times 10^{19}\ J}$$

8. $m = 2\ kg, E = ?$

$$E = mc^2$$

$$E = (2\ kg)\left(3 \times 10^8 \frac{m}{s}\right)^2$$

$$\boldsymbol{E = 1.8 \times 10^{17}\ J}$$

9. $KE_{classic} = \frac{1}{2}mv^2$

$$KE_{classic} = \frac{1}{2}(500\ kg)\left(0.90\left(3 \times 10^8 \frac{m}{s}\right)\right)^2$$

$$KE_{classic} = 1.82 \times 10^{19}\ J$$

$KE_{relativistic} = 5.82 \times 10^{19}\ J$ (see #7)

$$ratio = \frac{5.82 \times 10^{19}\ J}{1.82 \times 10^{19}\ J} = \boldsymbol{3.20}$$

10. $v_{EntE} = 0.9c, v_{KE} = 0.7c, v_{EntK} = ?$

$$v_{EntK} = \frac{v_{EntE} + v_{EK}}{1 + \frac{v_{EntE}v_{EK}}{c^2}}$$

$$v_{EntK} = \frac{0.9c + -0.7c}{1 + \frac{(0.9c)(-0.7c)}{c^2}}$$

$$\boldsymbol{v_{EntK} = 0.541c}$$

11. $v_{KE} = 0.7c, v_{TK} = 0.5c, v_{tE} = ?$

$$v_{TE} = \frac{v_{TK} + v_{KE}}{1 + \frac{v_{TK}v_{KE}}{c^2}}$$

$$v_{TE} = \frac{0.5c + 0.7c}{1 + \frac{(0.7c)(0.5c)}{c^2}}$$

$$\boldsymbol{v_{TE} = 0.889c}$$

12. $v_{KE} = 0.7c, v_{KS} = 0.5c, v_{SE} = ?$

$$v_{SE} = \frac{v_{SK} + v_{KE}}{1 + \frac{v_{SK}v_{KE}}{c^2}}$$

$$v_{SE} = \frac{-0.5c + 0.7c}{1 + \frac{(-0.5c)(0.7c)}{c^2}}$$

$$\boldsymbol{v_{SE} = 0.308c}$$

13. $u = -0.1c, \lambda_s = 650\ nm$

$$\lambda_{obs} = \lambda_s\sqrt{\frac{1 + \frac{u}{c}}{1 - \frac{u}{c}}}$$

$$\lambda_{obs} = (650\ nm)\sqrt{\frac{1 + \frac{-0.1c}{c}}{1 - \frac{-0.1c}{c}}} = \boldsymbol{588\ nm}$$