1. If a charged pion that decays in $10^{-8}$ second in its own rest frame is to travel 30 meters in the laboratory before decaying, the pion’s speed must be most nearly:

   A. $0.43 \times 10^8$ m/s
   B. $2.84 \times 10^8$ m/s
   C. $2.90 \times 10^8$ m/s
   D. $2.98 \times 10^8$ m/s
   E. $3.00 \times 10^8$ m/s

2. In an inertial reference frame $S$, two events occur on the $x$-axis separated in time by $\Delta t$ and in space by $\Delta x$. In another inertial reference frame $S'$, moving in the $x$-direction relative to $S$, the two events could occur at the same time under which, if any, of the following conditions?

   A. For any values of $\Delta x$ and $\Delta t$
   B. Only if $|\Delta x/\Delta t| < c$
   C. Only if $|\Delta x/\Delta t| > c$
   D. Only if $|\Delta x/\Delta t| = c$
   E. Under no condition

3. A tube of water is traveling at $1/2c$ relative to the lab frame when a beam of light traveling in the same direction as the tube enters it. What is the speed of light in the water relative to the lab frame? (The index of refraction of water is $4/3$).

   A. $1/2$ c
   B. $2/3$ c
   C. $5/6$ c
   D. $10/11$ c
   E. c

4. Two observers $O$ and $O'$ observe two events, $A$ and $B$. The observers have a constant relative speed of 0.8c. In units such that the speed of light is 1, observer $O$ obtained the following coordinates:

   Event A: $x = 3$, $y = 3$, $z = 3$, $t = 3$
   Event B: $x = 5$, $y = 3$, $z = 1$, $t = 5$

   What is the length of the space time interval between these two events, as measured by $O'$?

   A. 1
   B. $\sqrt{2}$
   C. 2
   D. 3
   E. $2\sqrt{3}$
A car of rest length 5 meters passes through a garage of rest length 4 meters. Due to the relativistic Lorentz contraction, the car is only 3 meters long in the garage's rest frame. There are doors on both ends of the garage, which open automatically when the front of the car reaches them and close automatically when the rear passes them. The opening or closing of each door requires a negligible amount of time.

5. The velocity of the car in the garage’s rest frame is:
   A. 0.4c
   B. 0.6c
   C. 0.8c
   D. greater than c
   E. not determinable from the data given

6. The length of the garage in the car’s rest frame is
   A. 2.4 m
   B. 4.0 m
   C. 5.0 m
   D. 8.3 m
   E. not determinable from the data given

7. Which of the following statements is the best answer to the question “Was the car ever inside a closed garage?”
   A. No, because the car is longer than the garage in all reference frames.
   B. No, because the Lorentz contraction is not a “real” effect.
   C. Yes, because the car is shorter than the garage in all reference frames.
   D. Yes, because the answer to the question in the garage’s rest frame must apply in all reference frames.
   E. There is no unique answer to the question, as the order of door openings and closings depend on the reference frame.
8. Which of the following is a Lorentz transformation. (Assume a system of units such that the velocity of light is 1.)

A. 

\[
\begin{align*}
    x' &= 4x \\
    y' &= y \\
    z' &= z \\
    t' &= 0.25t
\end{align*}
\]

B. 

\[
\begin{align*}
    x' &= x - 0.75t \\
    y' &= y \\
    z' &= z \\
    t' &= t
\end{align*}
\]

C. 

\[
\begin{align*}
    x' &= 1.25x - 0.75t \\
    y' &= y \\
    z' &= z \\
    t' &= 1.25t - 0.75x
\end{align*}
\]

D. 

\[
\begin{align*}
    x' &= 1.25x - 0.75t \\
    y' &= y \\
    z' &= z \\
    t' &= 0.75t - 1.25x
\end{align*}
\]

E. None of the above
9. A π⁺ meson (rest-mass energy 135 MeV) is moving with velocity 0.8c\ ˆk in the laboratory rest frame when it decays into two photons, γ₁ and γ₂. In the π⁺ rest frame, γ₁ is emitted forward and γ₂ is emitted backward relative to the π⁺ direction of flight. The velocity of γ₂ in the laboratory rest frame is

A. -1.0c \ ˆk
B. -0.2c \ ˆk
C. +0.8c \ ˆk
D. +1.0c \ ˆk
E. +1.8c \ ˆk

10. Tau leptons are observed to have an average half-life of Δt₁ in the frame S₁ in which the leptons are at rest. In an inertial frame S₂, which is moving at a speed v₁₂ relative to S₁, the leptons are observed to have an average half-life of Δt₂. In another inertial reference frame S₃, which is moving at a speed v₁₃ relative to S₁ and v₂₃ relative to S₂, the leptons have an observed half-life of Δt₃. Which of the following is a correct relationship among two of the half-lives, Δt₁, Δt₂, and Δt₃?

A. \( Δt₂ = Δt₁ \sqrt{1 - (v₁₂)^2/c²} \)
B. \( Δt₁ = Δt₃ \sqrt{1 - (v₁₃)^2/c²} \)
C. \( Δt₂ = Δt₃ \sqrt{1 - (v₂₃)^2/c²} \)
D. \( Δt₃ = Δt₂ \sqrt{1 - (v₂₃)^2/c²} \)
E. \( Δt₁ = Δt₂ \sqrt{1 - (v₂₃)^2/c²} \)

11. In inertial frame S, two events occur at the same instant in time and 3c minutes apart in space. In inertial frame S', the same events occur at 5c minutes apart. What is the time interval between the events in S'?

A. 0 min
B. 2 min
C. 4 min
D. 8 min
E. 16 min

12. The half life of a π⁺ meson at rest is 2.5 × 10⁻⁸ second. A beam of π⁺ mesons is generated at a point 15 meters from a detector. Only \( \frac{1}{2} \) of the π⁺ mesons live to reach the detector. The speed of the π⁺ mesons is

A. \( \frac{1}{2}c \)
B. \( \sqrt{\frac{2}{5}}c \)
C. \( \frac{2}{\sqrt{5}}c \)
D. c
E. 2c

13. An atom moving at a speed 0.3c emits an electron along the same direction with speed 0.6c in the internal rest frame of the atom. The speed of the electron in the lab frame is equal to:

A. 0.25c
B. 0.51c
C. 0.66c
D. 0.76c
E. 0.90c
14. Two spaceships approach Earth with equal speeds, as measured by an observer on Earth, but from opposite directions. A meterstick on one spaceship is measured to be 60 cm long by an occupant of the other spaceship. What is the speed of each spaceship, as measured by the observer on Earth?

A. 0.4c  
B. 0.5c  
C. 0.6c  
D. 0.7c  
E. 0.8c

15. A meter stick with a speed of 0.8c moves past an observer. In the observer’s reference frame, how long does it take the stick to pass the observer?

A. 1.6 ns  
B. 2.5 ns  
C. 4.2 ns  
D. 6.9 ns  
E. 8.3 ns

16. A beam of muons travels through the laboratory with speed $v = \frac{4}{5}c$. The lifetime of a muon in its rest frame is $\tau = 2.2 \times 10^{-6}$s. The mean distance traveled by the muons in the laboratory frame is

A. 530 m  
B. 660 m  
C. 880 m  
D. 1100 m  
E. 1500 m

17. An observer $O$ at rest midway between two sources of light at $x = 0$ and $x = 10$ m observes the two sources to flash simultaneously. According to a second observer $O'$, moving at a constant speed parallel to the $x$-axis, one source of light flashes 13 ns before the other. Which of the following gives the speed of $O'$ relative to $O$?

A. 0.13c  
B. 0.15c  
C. 0.36c  
D. 0.53c  
E. 0.62c