VicPhysics TEACHERS' NETWORK

Misconceptions on mass-energy relationship and strategies to address them

Google AI response
Many physics students mistakenly think that mass increases with speed or that rest mass and relativistic mass are distinct physical properties, failing to grasp that ($E_0 = mc^2$) applies to rest energy while the invariant mass (m) remains constant regardless of velocity.

Common Student Misconceptions

- **Relativistic Mass Increase:** Students think an object gets heavier as it moves faster.
- **Mass-Energy Equivalence Limits:** Students think mass-energy conversion only happens in nuclear reactions.
- **Photon Mass Confusion:** Students assume photons have zero energy because they have zero rest mass.
- **Invariance Confusion:** Students treat (m) as a variable that changes with the reference frame.

Strategies to Overcome Misconceptions

- **Use Invariant Mass:** Teach mass as a single, frame-independent property ($m = E_0/c^2$).
- **Drop Relativistic Mass:** Avoid teaching the concept of relativistic mass entirely.
- **Broaden Examples:** Apply ($E = mc^2$) to everyday bound systems like hot coffee or compressed springs.

Classroom Activity: The Particle Accelerator Role-Play
This activity helps students visually and conceptually separate **inertia (resistance to acceleration)** from **intrinsic mass**.

The Setup

1. Mark a straight line on the classroom floor to represent a particle accelerator track.
2. Designate one student as the **Proton** and another as the **Force Field**.

The Action

- **Phase 1 (Low Speed):** The Force Field gives the Proton a constant, gentle push. The Proton speeds up quickly and easily.
- **Phase 2 (High Speed):** As the Proton approaches the "speed of light," the Force Field pushes with the exact same constant strength. However, the Proton now barely speeds up at all.
  The Reflection & Discussion
  Ask the students: *"Why did the Proton slow down its acceleration? Did it get heavier?"*
  - **The Correction:** Explain that the Proton's intrinsic mass (its internal content) did not change. Instead, as momentum approaches infinity near the speed of light, a constant force yields diminishing returns in speed.
  - **The Takeaway:** The resistance to acceleration changes because of the geometry of spacetime, not because the particle gained physical matter.

ChatGPT response

For senior secondary physics students (such as VCE Physics), misconceptions about the mass-energy relationship usually arise because students encounter $E = mc^2$ as a memorable slogan rather than as one part of Einstein's broader relativistic framework. Research in physics education shows that many students retain Newtonian intuitions about mass, motion, and energy even after instruction in special relativity. A useful teaching approach is to treat these misconceptions explicitly and confront them with thought experiments, multiple representations, and comparisons between Newtonian and relativistic models.

The most common misconceptions and how to address them

Common misconception	Instructional strategy
"$E = mc^2$ means mass can be converted into energy." Students often think mass disappears and becomes energy.	Emphasise that mass is one form of energy. Use the idea that a system's mass reflects its total internal energy. Compare a charged battery with a discharged battery, or a hot object with a cooler one, and discuss why the higher-energy system has slightly greater mass.
Mass and energy are separate substances that transform into each other.	Introduce the concept of mass-energy equivalence: mass and energy are different measures of the same physical quantity. Use energy accounting tables before and after nuclear reactions.
A moving object has more mass. Students often learn or infer "relativistic mass."	Teach invariant (rest) mass consistently. Distinguish clearly between mass and total energy. Show that momentum and energy increase with speed while rest mass remains constant.
$E = mc^2$ applies only to nuclear reactions or atomic bombs.	Use everyday examples where adding energy increases mass slightly: heating a metal block, compressing a spring, or charging a battery. Stress that the effect is universal, though usually extremely small.
Photons have no energy because they have no mass.	Contrast rest mass with energy. Introduce photons as particles with zero rest mass but non-zero energy and momentum. Connect to the photoelectric effect and photon momentum.
The speed of light appears in the equation because light causes the energy.	Discuss why c^2 is a conversion factor linking units of mass and energy. Compare it with other conversion constants (e.g., 1 kWh = 3.6 MJ).
Energy released in nuclear reactions comes from destroyed matter.	Use mass defect calculations. Show that the total mass of products is less than that of reactants, and that the missing mass corresponds exactly to the released kinetic energy and radiation.
$E = mc^2$ gives the energy of any moving object. Students use it instead of kinetic energy formulas.	Differentiate rest energy $E_0 = mc^2$ from total energy and kinetic energy. Use comparison tables and worked examples where both $K = \frac{1}{2}mv^2$(approximation) and relativistic energy are discussed conceptually.
Mass is conserved separately from energy.	Replace the idea of separate conservation laws with conservation of total mass-energy. Analyse nuclear decay, pair production, and annihilation qualitatively.
More energy always means more speed.	Use relativistic graphs showing that as speed approaches c, added energy increasingly contributes to momentum and total energy rather than allowing speed to exceed c.

A useful conceptual sequence
For VCE-level students, the following progression tends to reduce confusion.
1. Start with Einstein's postulates
Before introducing $E = mc^2$, revisit:

- the invariance of the speed of light,
- time dilation,
- length contraction.

Students should see that relativity changes our ideas of space and time first, and that mass-energy equivalence emerges from the same framework.
2. Introduce rest energy
Present $E_0 = mc^2$ as:

- the energy associated with an object simply because it has mass,
- not the energy of motion.

Ask students: "If an object is completely at rest, can it still possess energy?"
3. Compare systems rather than isolated objects
Examples:

- charged vs discharged battery,
- compressed vs relaxed spring,
- hydrogen nucleus vs separate proton and neutron.

Students are more likely to understand that changes in internal energy change the mass of the entire system.

Diagnostic questions that reveal misconceptions
Question 1
A charged battery has a mass of 250.0000000 g. After it is fully discharged, what happens to its mass?

- A. It is unchanged.
- B. It decreases slightly.
- C. It increases slightly.
- D. It becomes zero.

Correct answer: B.
Question 2
A photon has zero rest mass. Which statement is correct?

- A. It has no energy.
- B. It has energy but no momentum.
- C. It has both energy and momentum.
- D. It has mass equal to E/c^2.

Correct answer: C.
Question 3
As a spacecraft accelerates from 0.8c to 0.9c, what increases?

- A. Its rest mass.
- B. Its total energy.
- C. The speed of light.
- D. The mass of light.

Correct answer: B.

Teaching strategies that are particularly effective

Use multiple representations

Represent the same situation with:

- words,
- energy bar charts,
- mass-energy accounting tables,
- graphs of energy vs speed,
- particle diagrams.

Contrast Newtonian and Einsteinian reasoning

For example:

Newtonian	Einsteinian
Mass is fixed and conserved separately.	Total mass-energy is conserved.
Energy can be added without changing mass.	Adding energy increases the mass of a system.
Speed can increase indefinitely.	Speed approaches c asymptotically.

Use thought experiments

The photon clock, pair production, and electron-positron annihilation are especially powerful because they force students to confront the inadequacy of Newtonian assumptions.

Encourage language precision

Many misconceptions are reinforced by phrases such as:

- "mass turns into energy,"
- "mass increases with speed."

Prefer:

- "the system's mass decreases as energy leaves the system,"
- "the object's total energy increases while its rest mass remains constant."

A three-level progression for VCE Physics

Level	Student understanding
Developing	Knows $E = mc^2$ but treats mass and energy as separate substances.
Proficient	Recognises that energy changes correspond to mass changes in systems and can explain nuclear energy qualitatively.
Advanced	Uses invariant mass consistently, distinguishes rest energy from kinetic energy, and explains why energy, momentum, and mass form a unified relativistic description.

For VCE teachers, the single most effective intervention is usually to replace the "mass becomes energy" narrative with a "system energy changes, therefore system mass changes" narrative. Students who understand that mass is a measure of a system's total energy content are far less likely to misuse $E = mc^2$ in examinations and are better prepared for later study of nuclear physics, particle physics, and modern physics.

General resources

(PDF) Energy and mass misconceptions by Peter Riggs, ANU

Understanding Relativistic Momentum and Special Relativity - Physics HSCPrep

Quora discussion on meaning of proper time and mass-energy relationships