CS 5: What Students Know

Part 1:

Threshold Concept Name: Quantum tunneling

What students know:

1. Classical Mechanics Limitations. Newtonian concepts of energy, force, and motion. The idea of potential energy barriers in chemical reactions. the particle cannot cross the barrier.

2. Quantum Mechanical Basics. Wave–particle duality: matter has both wave and particle properties (de Broglie wavelength). The uncertainty principle and its qualitative meaning.

Schrödinger equation: form, meaning of ψ, and the idea of probability density

Bound and unbound states in simple systems (particle in a box, harmonic oscillator).

3. Potential Energy Concepts. Potential energy curves for molecular systems. The meaning of barrier height and activation energy in reaction profiles. Relationship between molecular vibrations and energy levels.

4. Basic Spectroscopy & Molecular Motions. Vibrational, rotational, and translational energy quantization. Energy level diagrams and allowed transitions.

5. Chemical Kinetics Background. The Arrhenius equation and the concept of activation energy.

Transition state theory (TST) and potential energy surfaces. Limitations of classical rate theories at low temperatures.

6. Mathematical Tools. Handling exponential functions and interpreting decay terms.
Understanding of boundary conditions for wavefunctions. Familiarity with basic differential equations in physics/chemistry contexts.

What Students Don't Know:

1. Non-classical Barrier Crossing, They don’t yet know that particles can cross barriers, due to their wave nature. Their mental model is still classical: “If you don’t have enough energy, you stop.”

2. Exponential Wavefunction Decay in Barriers. They have not seen in detail how the Schrödinger equation produces evanescent (decaying) wavefunctions inside a barrier.

The meaning of imaginary wavevector (κ) in the barrier region is new.

3. Quantitative Tunneling Probability, they don’t know the formula: or how mass, barrier width, and energy gap affect tunneling probability. They may know exponentials from decay processes, but not in the context of spatial wavefunctions.

4. Connection to Reaction Rates
They haven’t yet linked tunneling to non-Arrhenius temperature dependence in chemical kinetics. They may know about isotope effects but not that tunneling explains large H/D differences at low T.

5. Real-World Chemical Examples
They might have heard of tunneling in nuclear decay or scanning tunneling microscopy, but, proton tunneling in acid–base reactions, electron tunneling in redox chemistry, enzyme-catalyzed hydrogen transfers etc. are usually unfamiliar with.

6. Visualization of Probability Leakage: They do not have an intuitive picture of a wavefunction “leaking” through a barrier and emerging on the other side. Most still imagine barriers as rigid walls unless energy is sufficient.

7. Mathematical Mindset Shift: They have not yet embraced that quantum probability amplitudes allow “forbidden” events with small but non-zero probabilities.

The interpretation of boundary conditions in multi-region Schrödinger solutions is still abstract.

Principles:

1. Wave–Particle Duality: Particles such as electrons, protons, and atoms have wave-like properties (de Broglie wavelength). Because they are described by a wavefunction ψ
ψ(x), they are not strictly localized, allowing their presence in classically forbidden regions.

2. Schrödinger Equation Solutions. Time-independent Schrödinger equation:

3. Principle of Probability Leakage. The probability density. If the barrier width is small enough, the “tail” overlaps with the far side, giving a non-zero tunneling probability.

4. Conservation of Energy:
Energy is conserved overall: the particle does not “gain” energy to cross the barrier — instead, its wavefunction amplitude allows crossing without classical over-the-barrier motion.

5. Dependence on Key Parameters:
Barrier Width: Narrower barriers increase tunneling probability. Lower barriers increase probability.

6. Quantum Superposition:
The particle exists in a superposition of “reflected” and “transmitted” states until measurement.

The transmission coefficient T. T gives the probability of detection beyond the barrier.

7. WKB Approximation:
Semiclassical method to estimate tunneling probability:

8. Principle of Applicability Across Scales. Same quantum principles explain:

Microscopic tunneling: proton/electron transfer in chemistry.

Macroscopic quantum effects: superconducting tunneling in Josephson junctions.
Nuclear tunneling: alpha decay.

Part 2:

Q. What is the correct taxonomy to learn quantum tunneling?

Answer: To learn quantum tunneling effectively, a combination of Bloom's Taxonomy and Fink's Taxonomy provides a robust framework. Bloom's taxonomy helps categorize cognitive skills, while Fink's taxonomy focuses on significant learning experiences. A strong understanding of quantum tunneling requires moving from basic recall to applying the concept, analyzing its implications, and even evaluating its role in various technologies.

Q. Generate case study using Bloom, Fink and SOLO. Build a comparison table on how they differ from each other.

Answer:
According to Bloom:

Remembering:
Start with the basic definition of quantum tunneling, understanding that it's a quantum mechanical phenomenon where particles can pass through potential barriers even if they lack the classical energy to do so.
Understanding:
Grasp the concept of wave-particle duality and how it enables tunneling. Learn about the mathematical descriptions and probability of tunneling.
Applying:
Apply the concept to real-world examples like scanning tunneling microscopes (STMs) or nuclear fusion in stars.
Analyzing:
Analyze the factors affecting tunneling probability, such as barrier height and width, and how they influence the process.
Evaluating:
Evaluate the significance of tunneling in various technologies and scientific theories, understanding its importance in fields like semiconductor physics and radioactive decay.
Creating:
Potentially, explore how to design experiments to further investigate or demonstrate tunneling or propose new applications based on the principles of tunneling.

According to Fink:

Foundational Knowledge:
Ensure a strong foundation in classical mechanics, quantum mechanics, and wave behavior.
Application:

Apply the concept of tunneling to practical examples and understand its role in different technologies and phenomena.
Integration:
Connect the concept of tunneling with other physics concepts, such as the wave-particle duality, potential barriers, and energy levels.
Human Dimension:
Recognize the importance of tunneling in phenomena like nuclear fusion, which is crucial for stars and our understanding of the universe.
Caring:
Develop an appreciation for the elegance and counter-intuitive nature of quantum mechanics and the importance of tunneling in various scientific and technological advancements.
Learning How to Learn:
Develop the ability to learn and apply new concepts in physics and other scientific fields by understanding the process of quantum tunneling.

According to Solo:

While Bloom's and Fink's taxonomies are more commonly used in this context, the SOLO Taxonomy can also be helpful. It focuses on the structure of observed learning outcomes. You could use it to assess the depth of understanding, moving from:
Pre-structural: Lacking understanding of tunneling.
Uni-structural: Understanding a single aspect of tunneling, like the definition.
Multi-structural: Understanding multiple aspects of tunneling, like the definition, wave-particle duality, and a simple application.
Relational: Understanding how different aspects of tunneling are related and how it connects to other concepts.
Extended Abstract: Applying tunneling to complex situations, analyzing its implications, and potentially even proposing new applications.

Part 3:

Reflection questions for evaluations:

I. Conceptual Understanding:
What is quantum tunneling? (Explain the phenomenon where a particle can pass through a potential barrier even if it doesn't have enough energy classically)
How does quantum tunneling differ from classical mechanics? (Relate it to the limitations of classical physics and the wave-particle duality)
Describe the relationship between wave function and potential barrier in tunneling. (How does the wave function behave when encountering a barrier, and what does it mean for the probability of tunneling?)

What are the key physical parameters that influence the tunneling probability? (Barrier height, width, and particle energy)
Why is quantum tunneling more prominent for lighter particles like electrons? (Relate this to the de Broglie wavelength and kinetic energy)
Explain the concept of a "tunneling current" in the context of a scanning tunneling microscope (STM).
II. Mathematical Aspects:
What is the transmission coefficient? (Explain how it's calculated and what it represents)
How can the tunneling probability be calculated for a rectangular potential barrier? (Relate this to the solution of the time-independent Schrödinger equation)
What are the assumptions made in the derivation of the tunneling probability formula? (e.g., the potential barrier is rectangular and static)
How can the tunneling probability be modified for different barrier shapes (e.g., triangular, parabolic)?
III. Applications and Phenomena:
Give examples of physical phenomena where quantum tunneling is observed. (Alpha decay, nuclear fusion, STM)
Explain the role of tunneling in nuclear fusion.
Describe how the scanning tunneling microscope utilizes quantum tunneling.
How does tunneling contribute to radioactive decay?
Explain the concept of a "tunnel diode" and its applications.
Discuss the relevance of tunneling in quantum computing.
IV. Advanced Questions:
How does tunneling affect the kinetics of chemical reactions? (Consider the heavy atom isotope effect)
What are the limitations of the simple rectangular barrier model for tunneling? (Real-world barriers are often more complex)
Can you discuss the concept of frustrated total internal reflection in the context of tunneling?
How does the concept of tunneling relate to the Heisenberg uncertainty principle?
Discuss the challenges in experimentally verifying quantum tunneling in certain systems.
What are some areas where quantum tunneling is still an active research topic?

Learning Outcome Map for Understanding Quantum Tunneling (using a combination of Bloom's Revised Taxonomy and SOLO Taxonomy):

This map provides a hierarchical progression of learning outcomes for grasping the concept of quantum tunneling, from basic recognition to deep conceptual understanding and application.
Level 1: Prestructural / Remembering (Bloom's)
At this initial stage, the learner has little or no grasp of quantum tunneling. The focus is on recognizing and recalling basic terms and concepts that serve as prerequisites.
Learning Outcomes:

Define quantum mechanics in a general sense.
Identify the concept of wave-particle duality as it relates to quantum particles.
Recall the existence of the Schrödinger Equation, though not necessarily its mathematical form.
List some areas where quantum mechanics plays a role (e.g., modern technologies, atomic behavior).

Level 2: Unistructural / Understanding (Bloom's)

Here, the learner grasps the core idea of quantum tunneling but may not yet see the connections between supporting concepts.

Learning Outcomes:

State the primary concept of quantum tunneling: that a particle can pass through a potential energy barrier even if it classically lacks the energy to do so.
Describe the wave-like behavior of particles that makes tunneling possible.
Explain the role of the potential barrier in quantum tunneling.
Give a simple example where quantum tunneling occurs (e.g., radioactive decay, field emission).

Level 3: Multistructural / Understanding & Applying (Bloom's)

At this level, the learner connects several ideas related to quantum tunneling and can use that understanding in basic applications.

Learning Outcomes:

Summarize the conditions necessary for quantum tunneling to occur.
Relate wave-particle duality to the probability of tunneling through a barrier.
Compare and contrast the behavior of a particle in quantum tunneling with its behavior in a classical scenario where it lacks the energy to overcome a barrier.
Given a simplified scenario, qualitatively predict how changes in the barrier's width or height would affect the probability of tunneling.
Identify applications of quantum tunneling, such as the scanning tunneling microscope (STM).

Level 4: Relational / Analyzing & Evaluating (Bloom's)

At this stage, the learner understands the relationships between the concepts and can critically evaluate information related to quantum tunneling.

Learning Outcomes:

Analyze how the wave function's behavior changes as a particle tunnels through a barrier.
Differentiate between various types of quantum tunneling and their characteristics.
Critique the common misconception that energy is lost during quantum tunneling, emphasizing energy conservation.
Evaluate the advantages and limitations of applying quantum tunneling principles in various technological contexts.
Justify the use of quantum tunneling in the functioning of devices like the STM.

Level 5: Extended Abstract / Creating (Bloom's)

This highest level involves generating new ideas, designs, or solutions using the knowledge and understanding of quantum tunneling.

Learning Outcomes:

Propose novel applications for quantum tunneling in emerging technologies.
Design (even conceptually) an experiment to investigate a specific aspect of quantum tunneling.
Synthesize information from different areas of physics to explain complex quantum phenomena involving tunneling. Communicate the societal impact of quantum tunneling and related technologies to a non-technical audience.

This map can be used to guide instruction, design assessments, and help learners track their progress in understanding quantum tunneling. Remember that learning is often iterative, and learners may revisit earlier levels as they deepen their understanding.