Quantization and Tunnelling

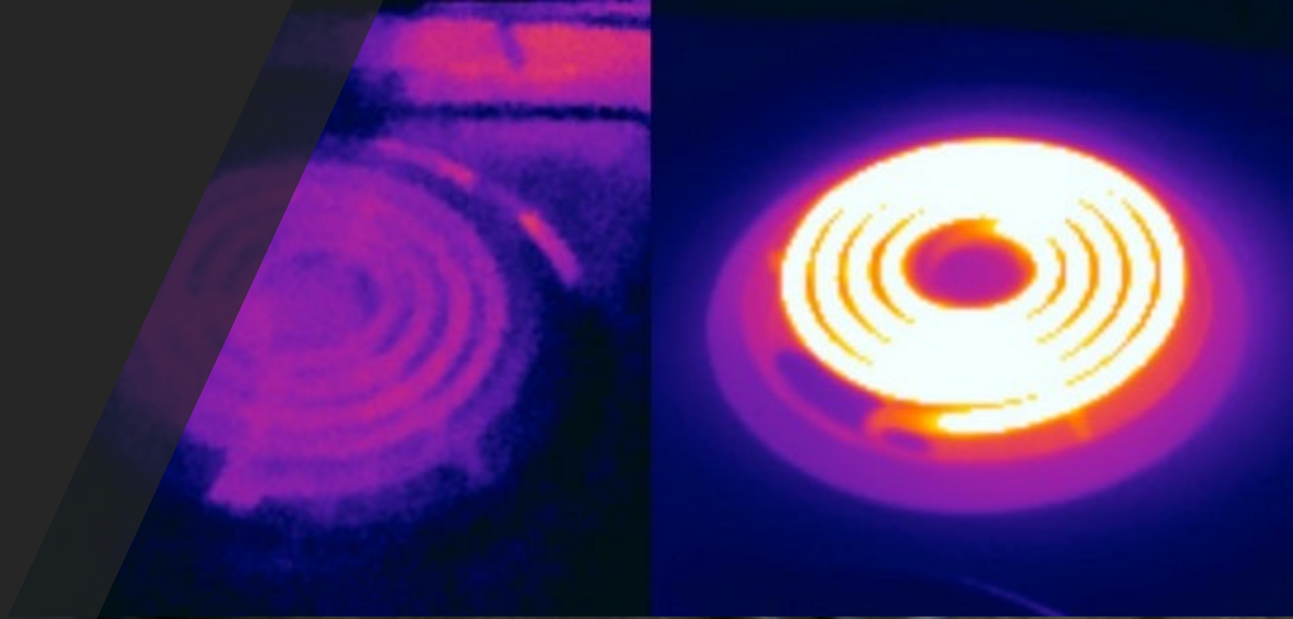
Applications to Quantum Technologies

Outline

- Quantization
  - History of Quantization
  - Quantum Information Storage
  - Quantum Information Communication
- Quantum Tunnelling
  - Quantum Tunnelling
  - Tunnelling Probes
  - Optimization and AI

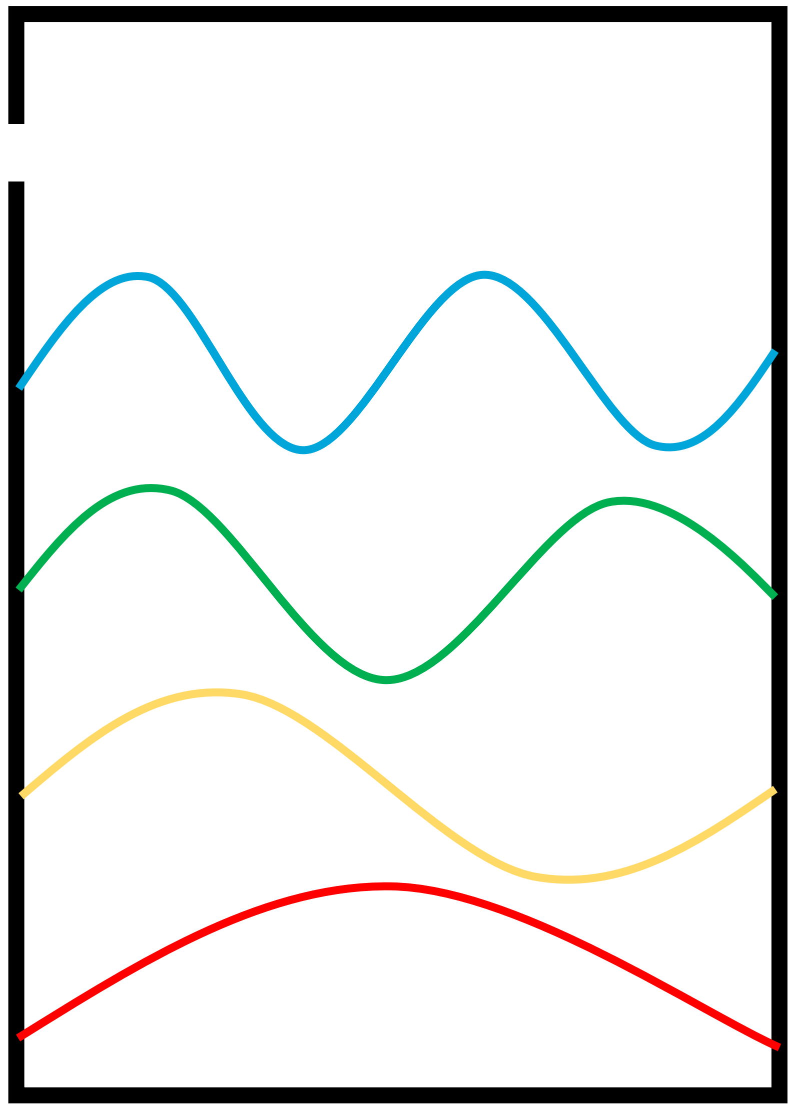
History of Quantization

- Near the end of the 19^{th} century, physicists believed nature had been largely explained
- One remaining unsolved problem was the glowing of hot objects



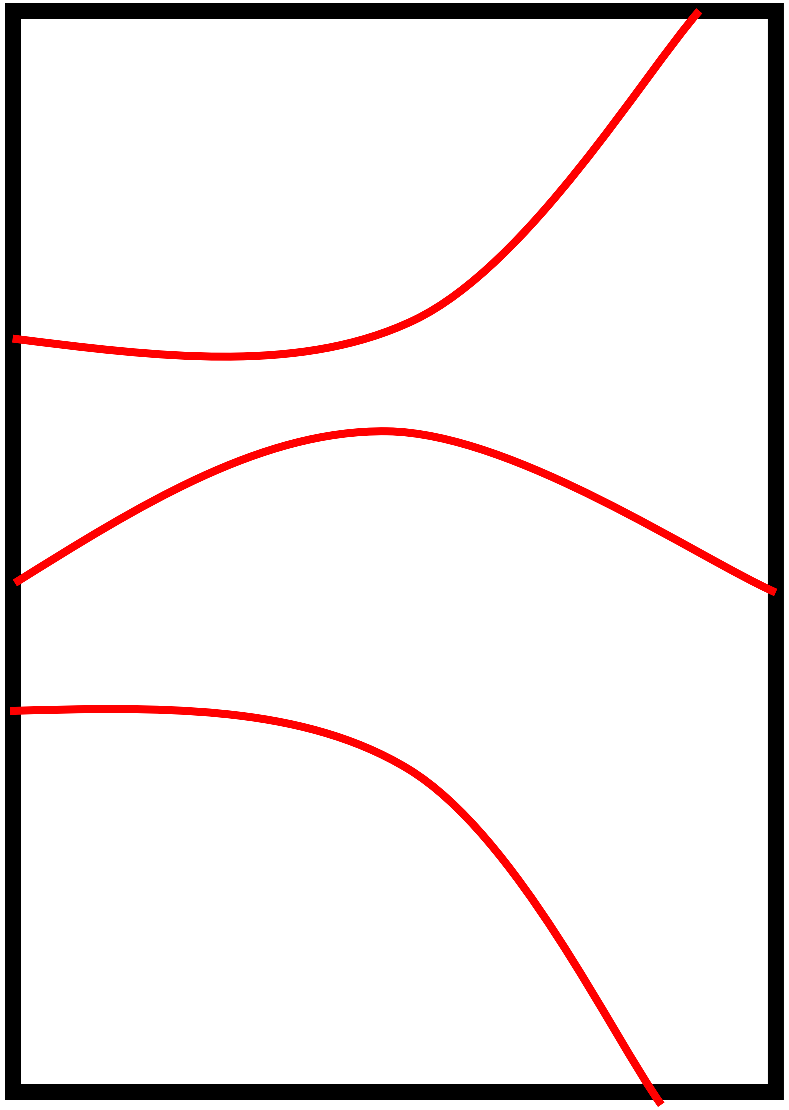
History of Quantization

- Light is emitted by objects, with a spectrum that depends on temperature
- Classical physics allows light of any wavelength to have any energy
- A ‘black body’ absorbs light of any wavelength



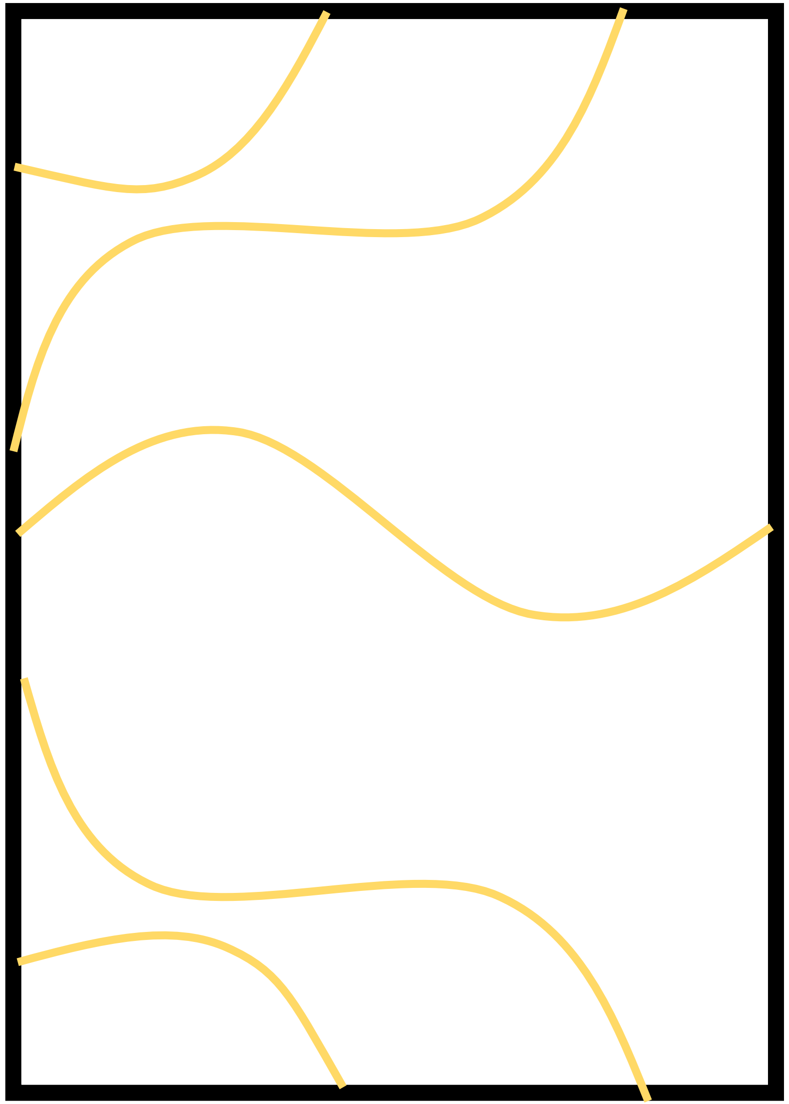
History of Quantization

- A box which is heated will radiate light inside the box
- Light which is emitted from one wall will be absorbed by another
- The spectrum of light inside the box will be equal to the number of waves that can fit between these walls



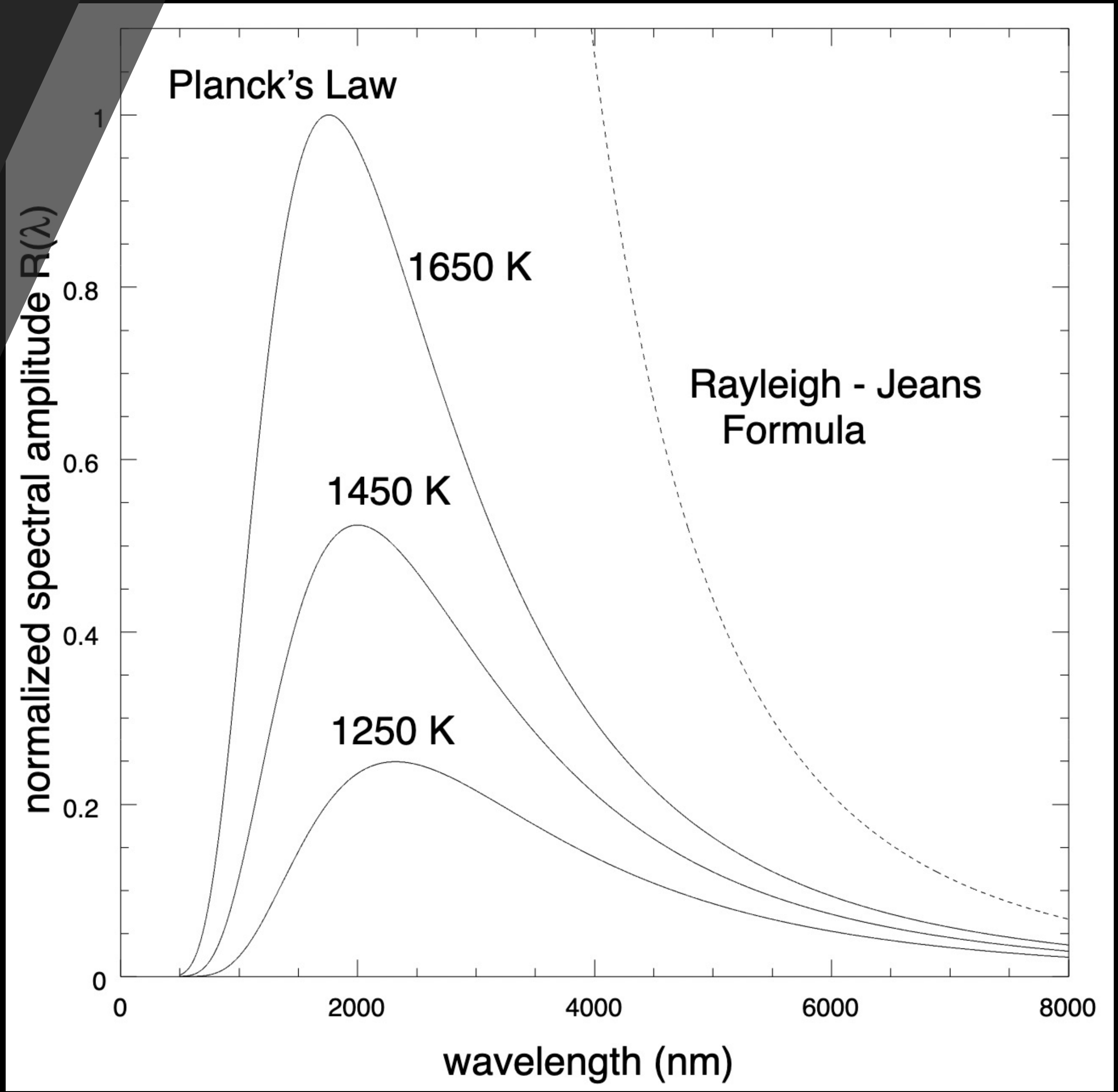
History of Quantization

- Therefore, as the wavelength decreases more waves can fit within this box
- This implies that the spectrum of light increases as wavelength decreases
- This does not match reality



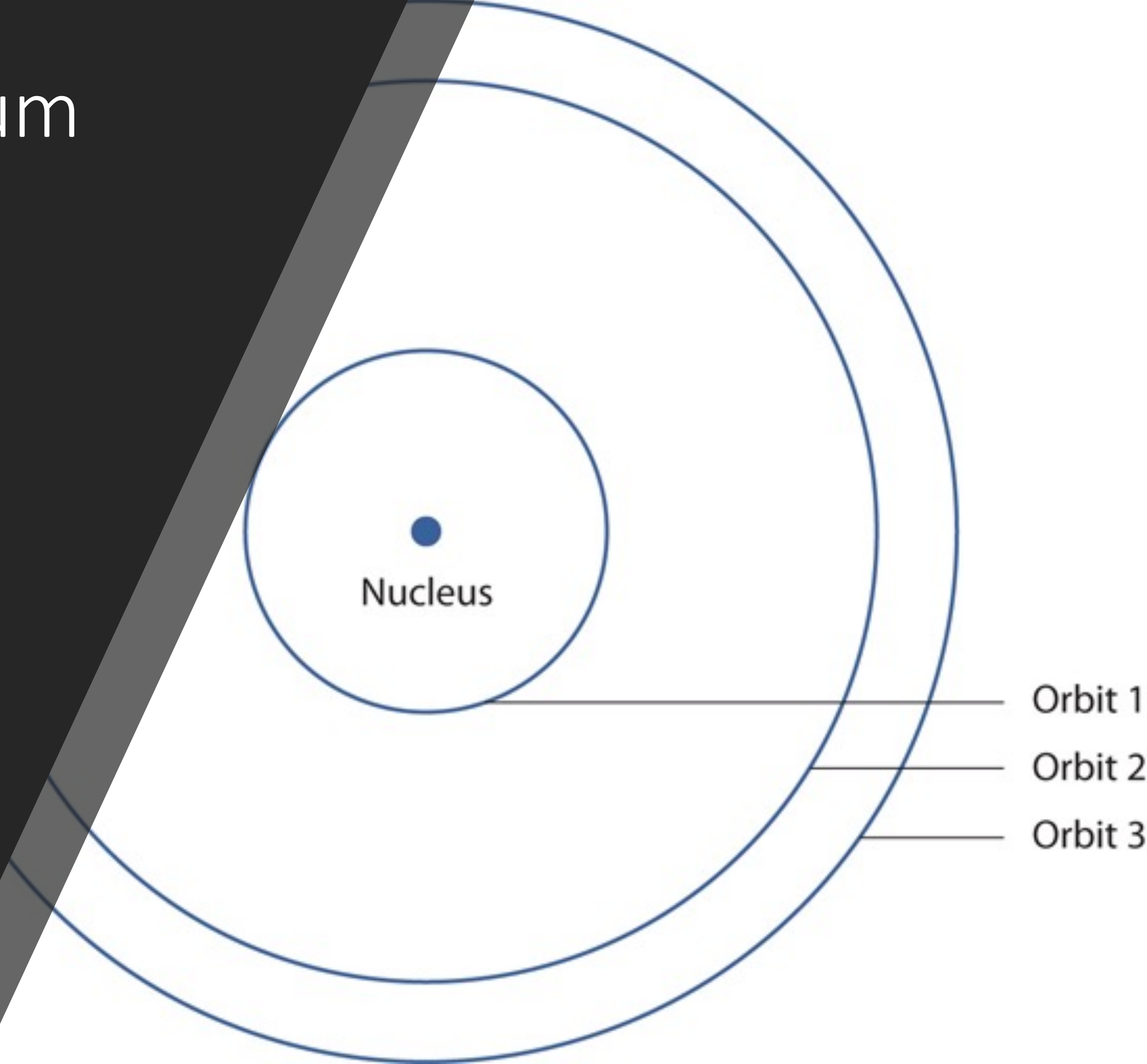
History of Quantization

- This problem was solved by Max Plank, who observed that the correct spectrum could be created if energy is quantized by wavelength
- That means that light cannot come in any energy, but only in specific chunks



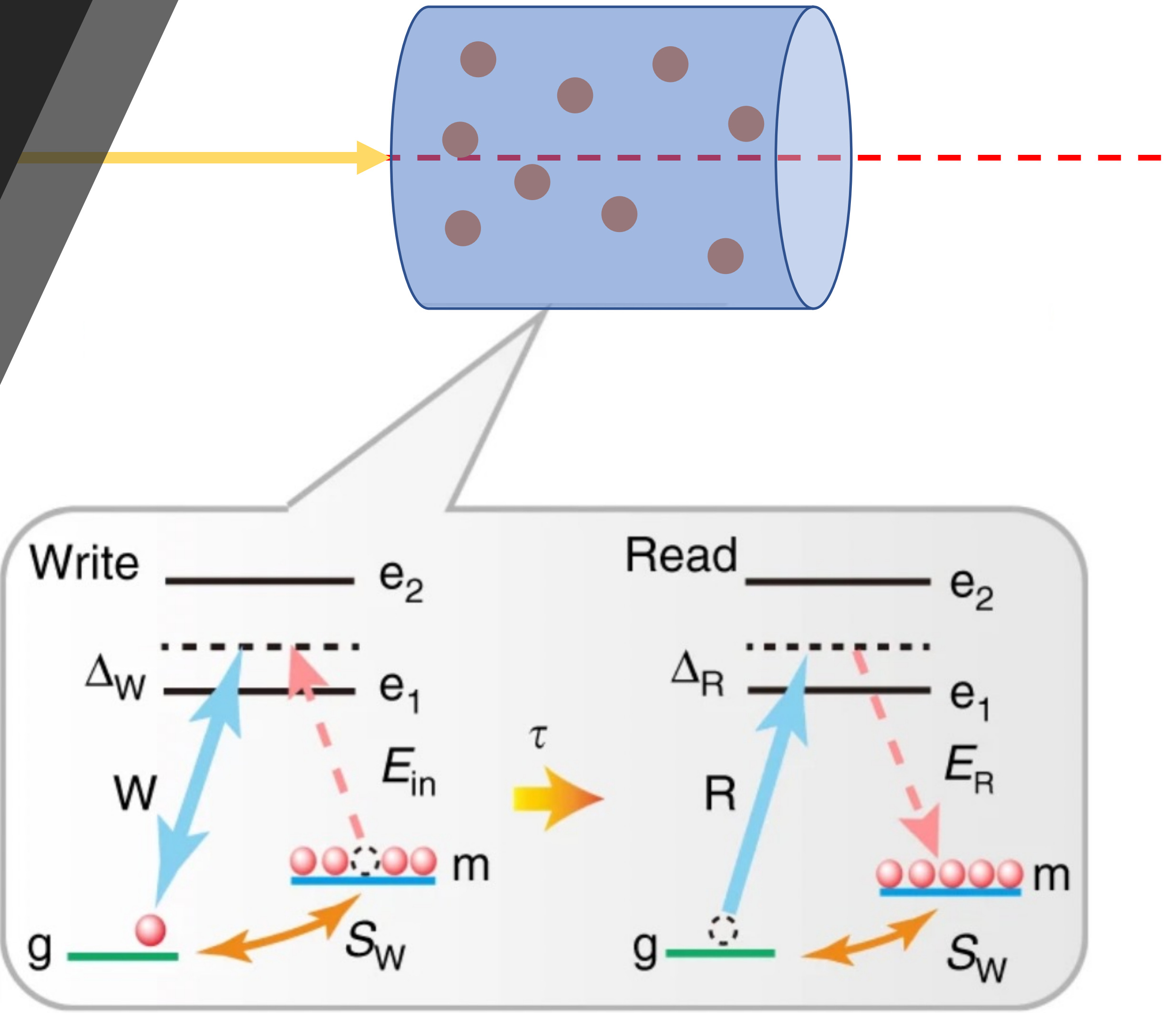
History of Quantum Mechanics

- At the end of the 19th century, physicists understood that the atoms contained a nucleus surrounded by electrons
- In 1913, Niels Bohr suggested that electrons can only exist in particular, stable energy levels



Quantization – Rubidium Atoms

- One quantized system which can store information is in Rubidium atoms
- A laser pulse can be used to excite electrons in the Rubidium, information is stored in the polarization of light
- This is a quantum memory, can we apply this technique to classical information?



Information Theory

- All computers can be considered a box which takes numbers, written in binary numbers, and transforms these numbers by some rule
- Information is also stored in binary

$|0\rangle$ → $\hat{U}|0\rangle$ → $|1\rangle$

Input | Output

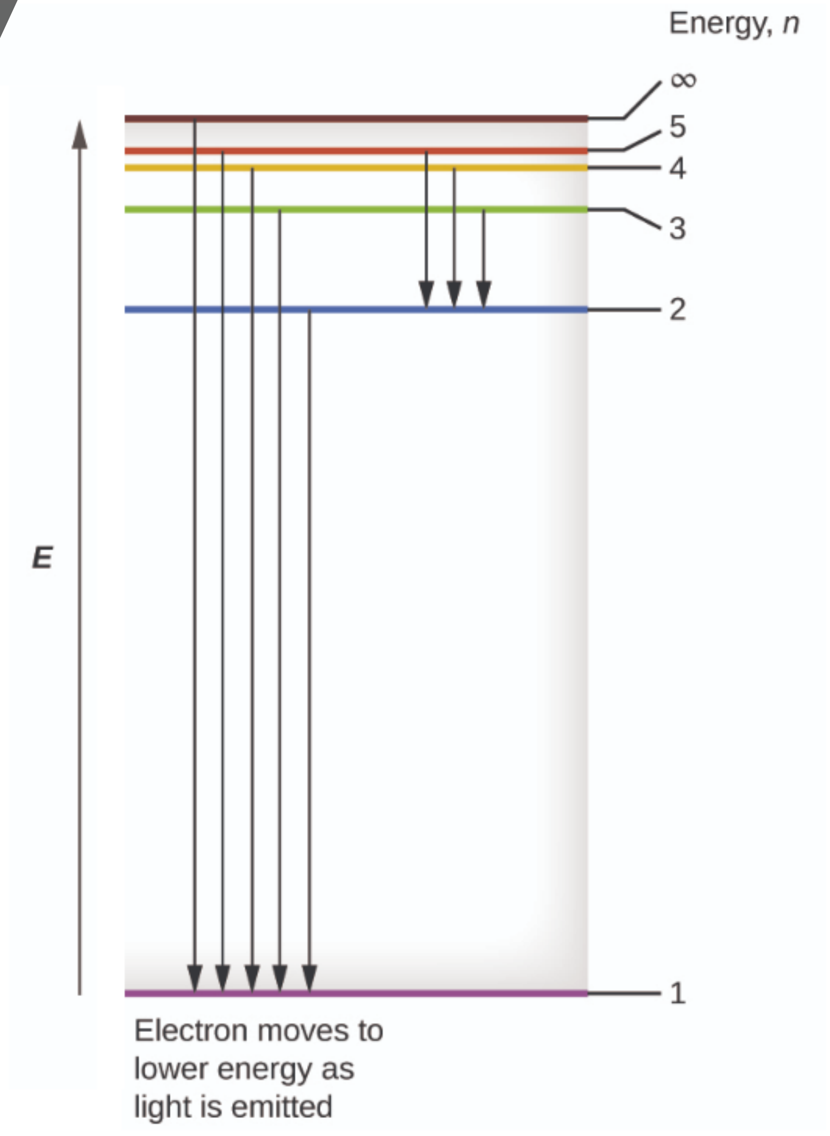
A computer is an *information processor*

Classical Information Storage

- In electronics, information is stored as high and low voltages
- Modern flash storage sets voltage levels in different cells
- These voltage levels are continuous
- Voltages drift over time and are susceptible to interference

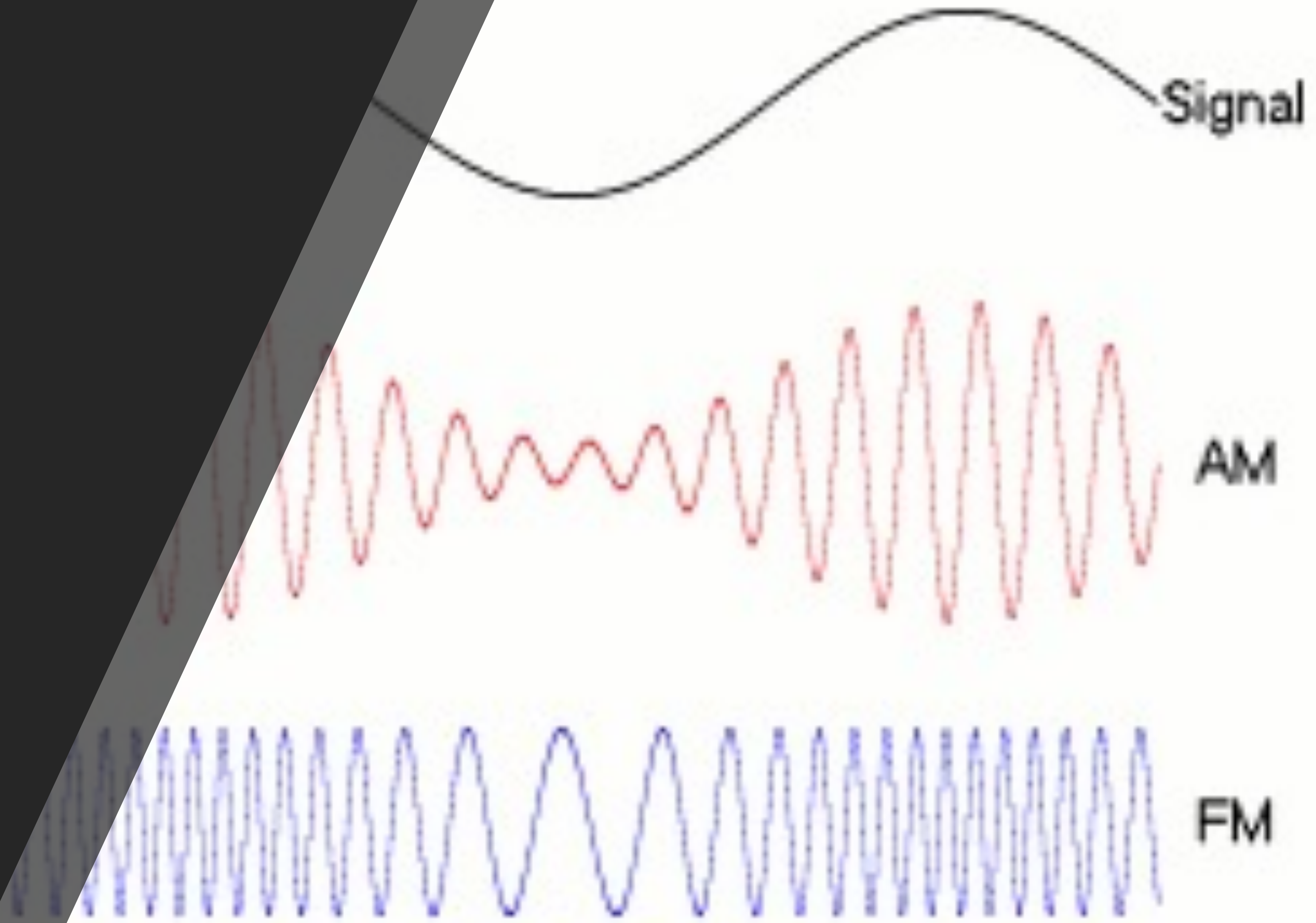
Quantized Information Storage

- In the classical world, these discrete energy levels are so close, that they appear continuous
- These energy levels can be leveraged to store information in a truly quantized manner
- Quantum-enabled information storage can leverage these discrete energy levels



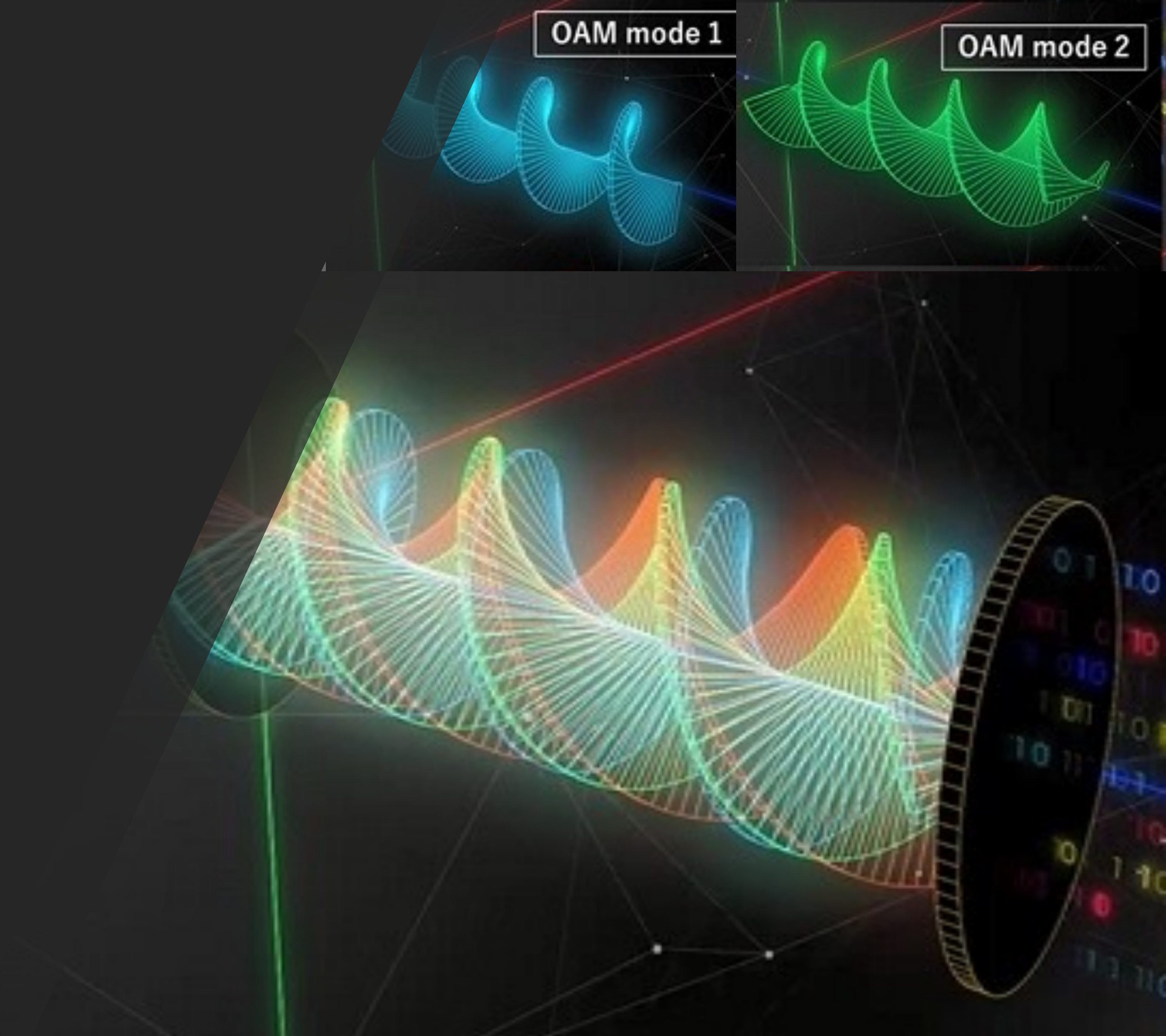
Classical Communication

- Similar issues exist in data communication
- Information is transmitted by modulating the amplitude of a light or electrical signal
- We can encode information in either amplitude or in frequency changes to a base signal



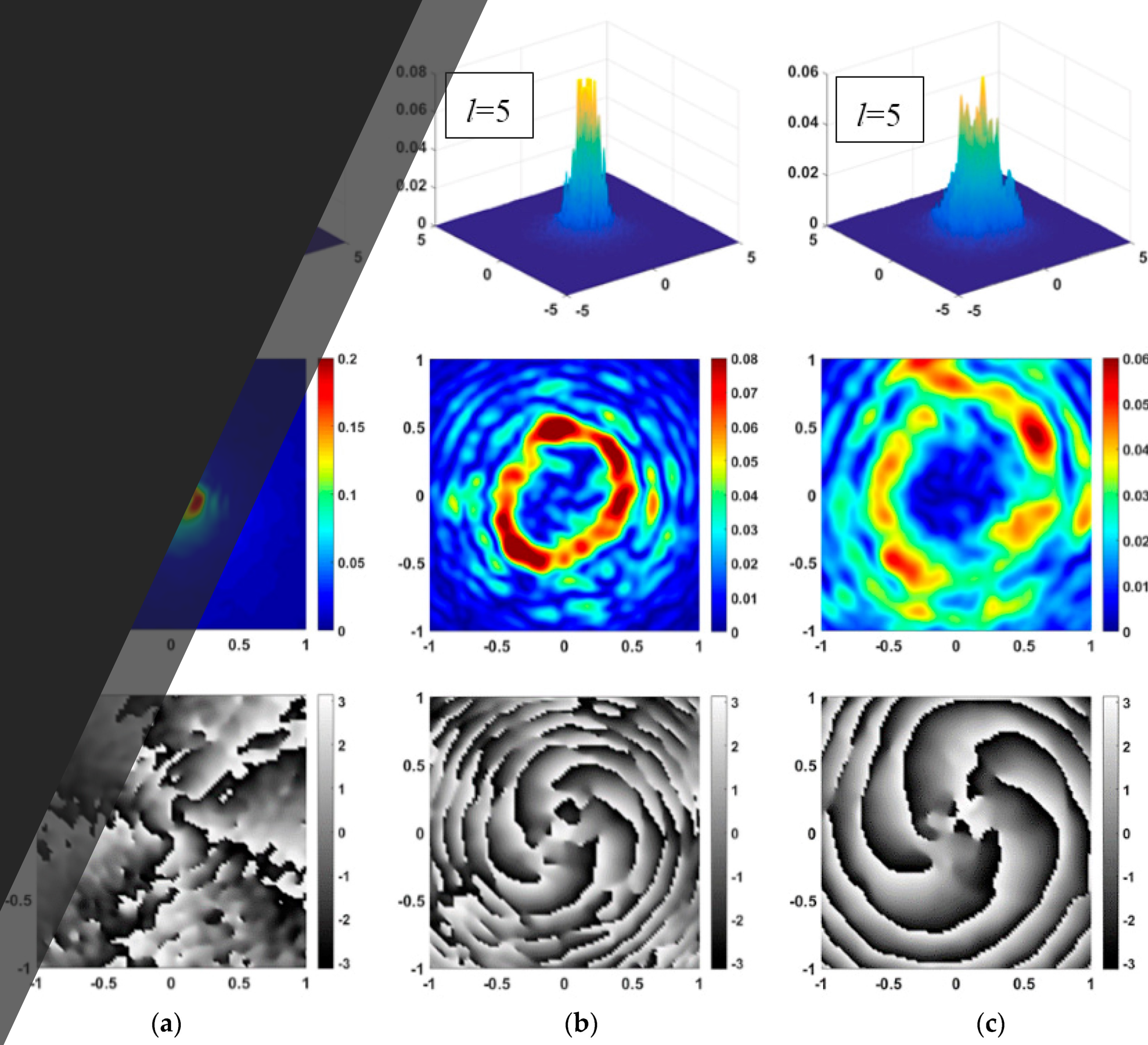
Quantization - Communication

- A photon can be prepared in an orbital angular momentum state
- These quantized modes can be used to encode information
- Data-transfer rates can be increased



Quantization - Communication

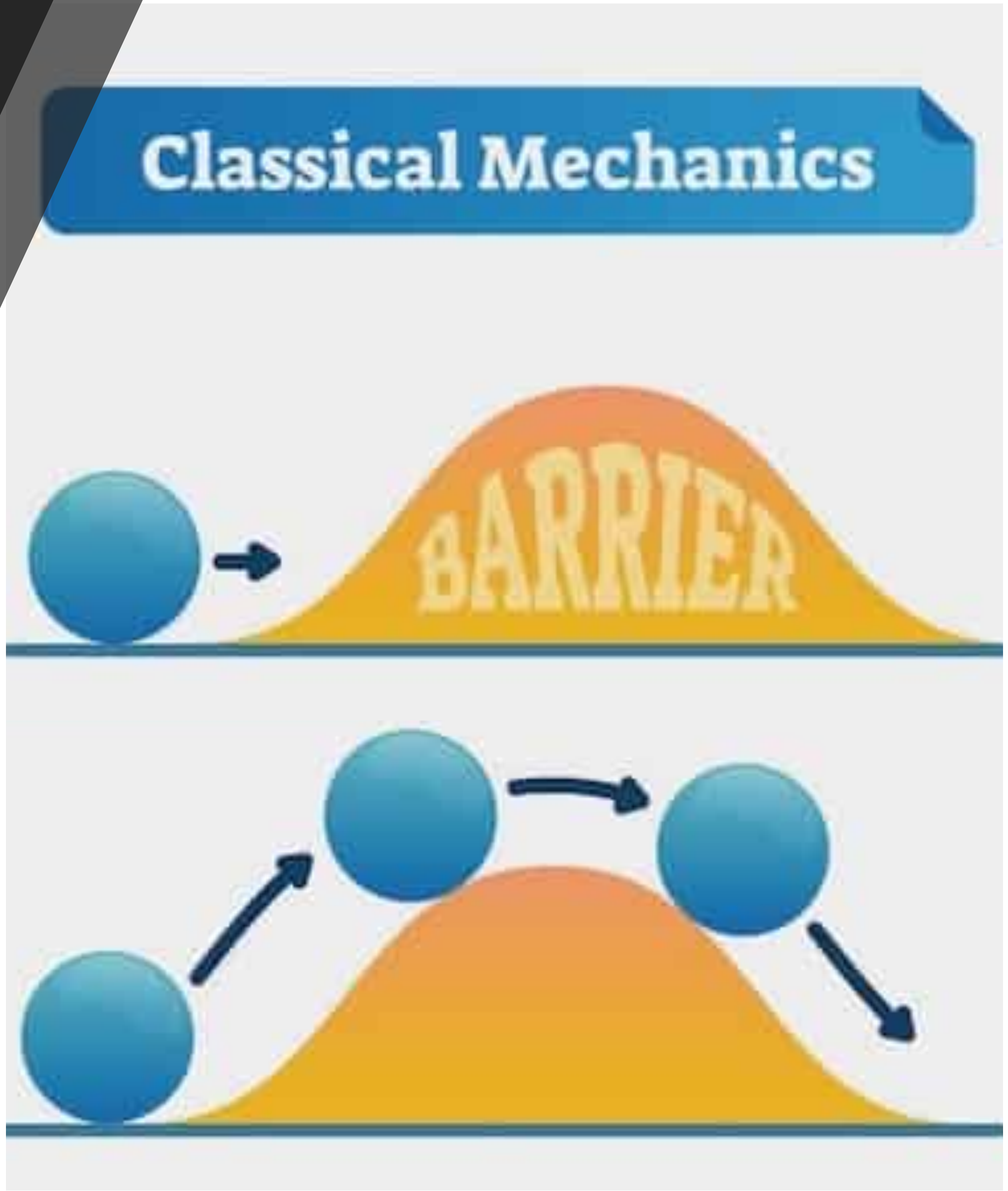
- Free-space communication is susceptible to atmospheric disturbance
- Quantized orbital angular momentum states are robust to atmospheric turbulence
- Ground-space communication travels through 90 km of atmosphere



What other problems would benefit from using quantization?

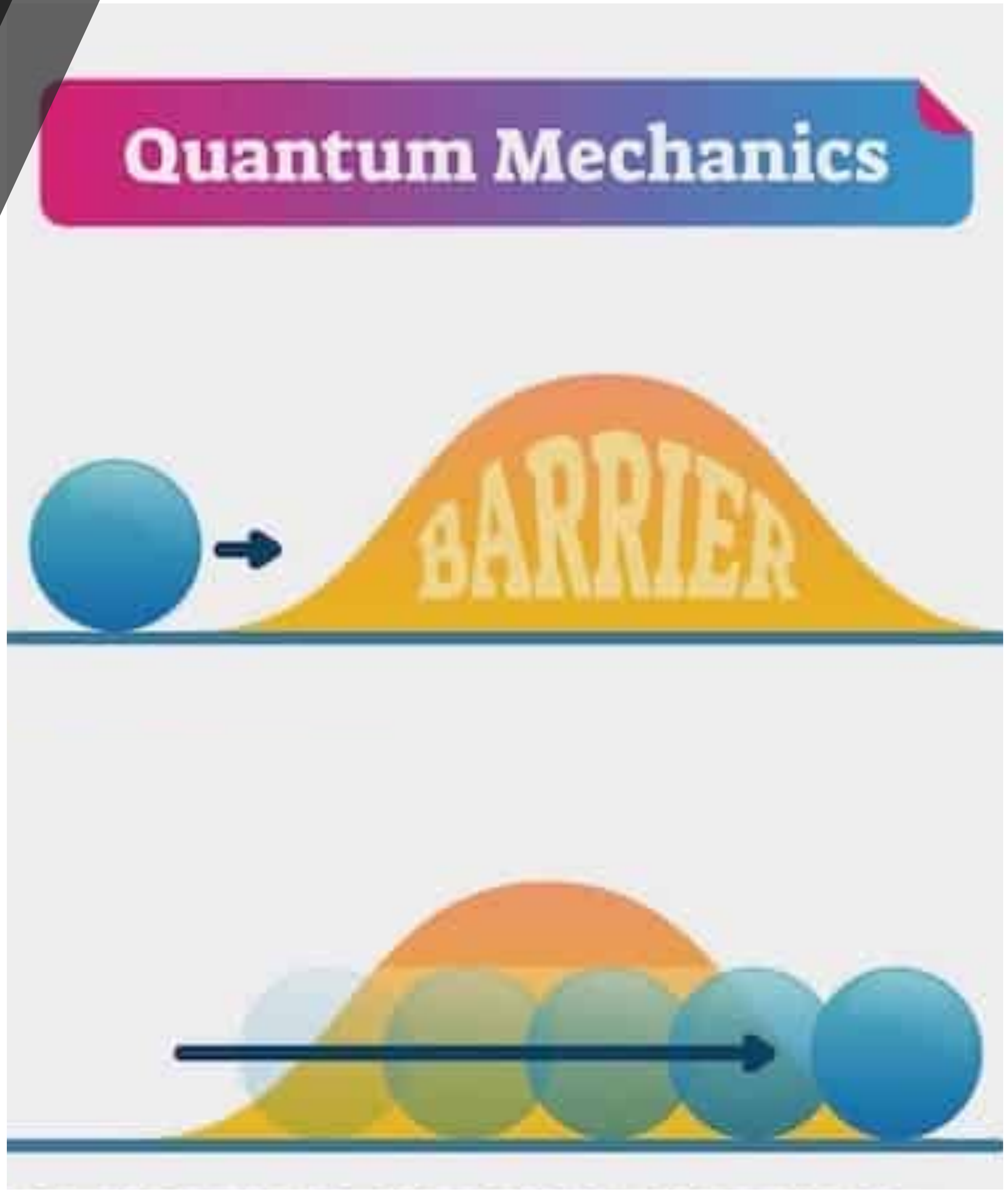
Quantum Tunnelling

- Objects our everyday experience require some energy to overcome a barrier
- A ball can only roll over a barrier if it has enough energy
- An object will insufficient energy will never pass over a barrier



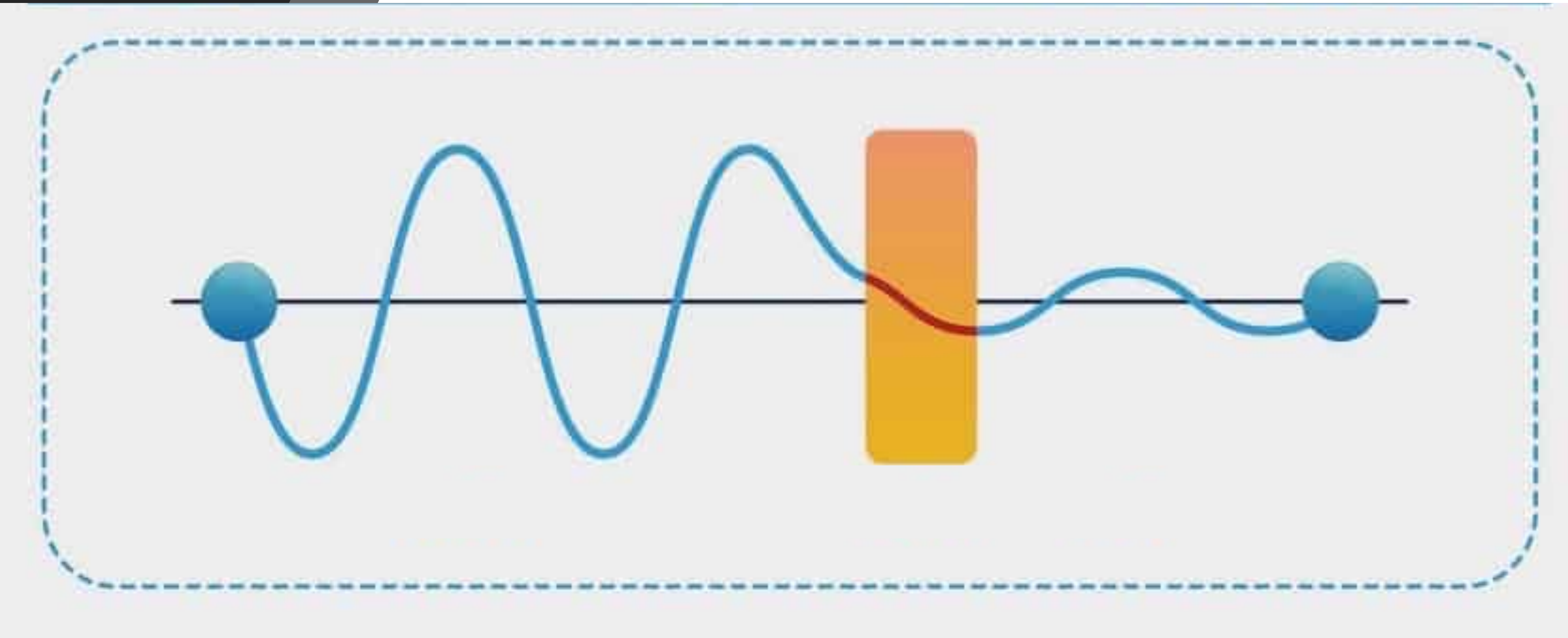
Quantum Tunnelling

- In the quantum regime, we find that this is not true
- Objects like particles, will not bounce off barriers (like a molecule)
- Instead, quantum objects can tunnel through these barriers
- In the particle example, an electron can tunnel through a molecule



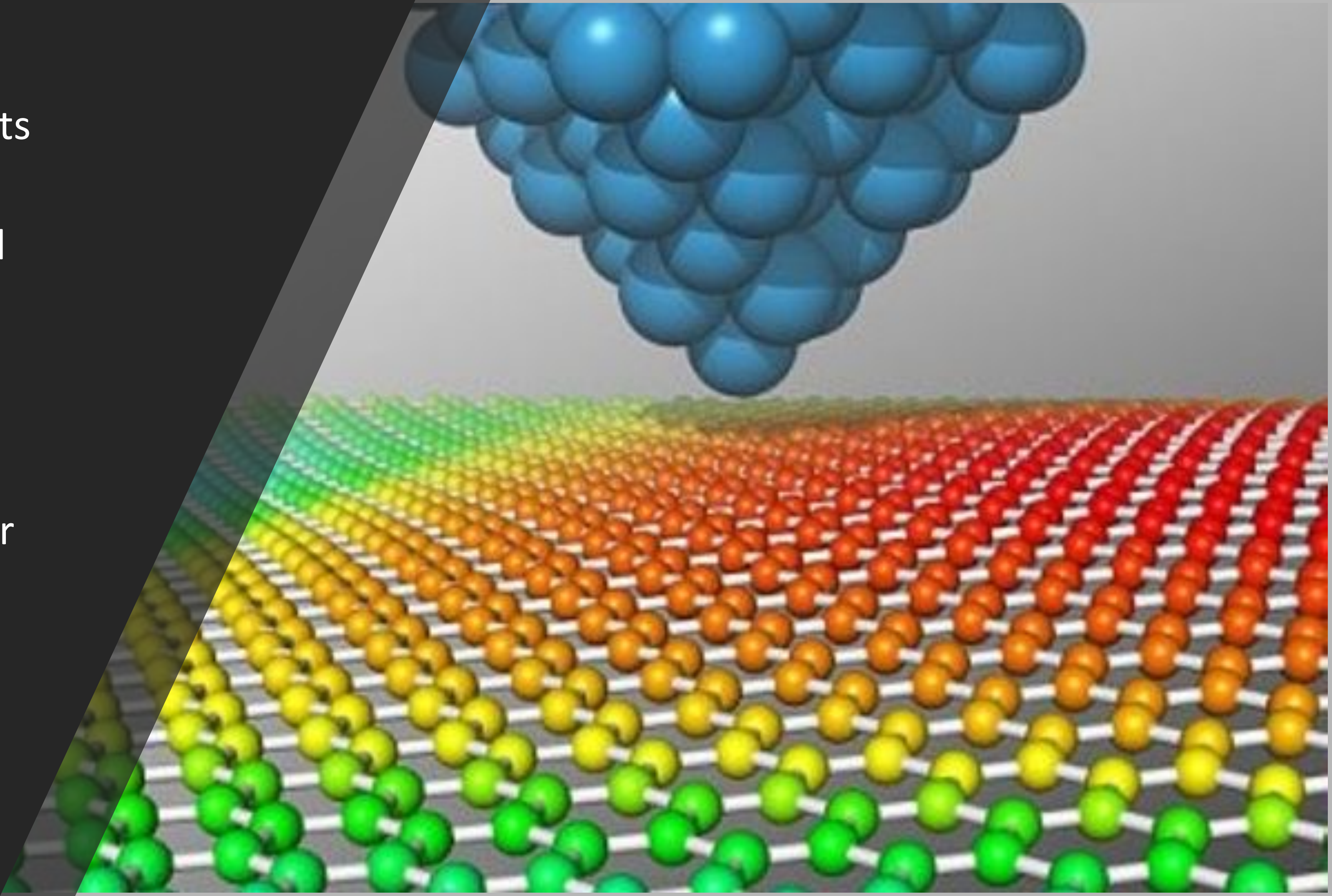
Quantum Tunnelling

- A quantum particle has a probability of passing through this barrier
- The particle which tunnels will be modified by the barrier itself



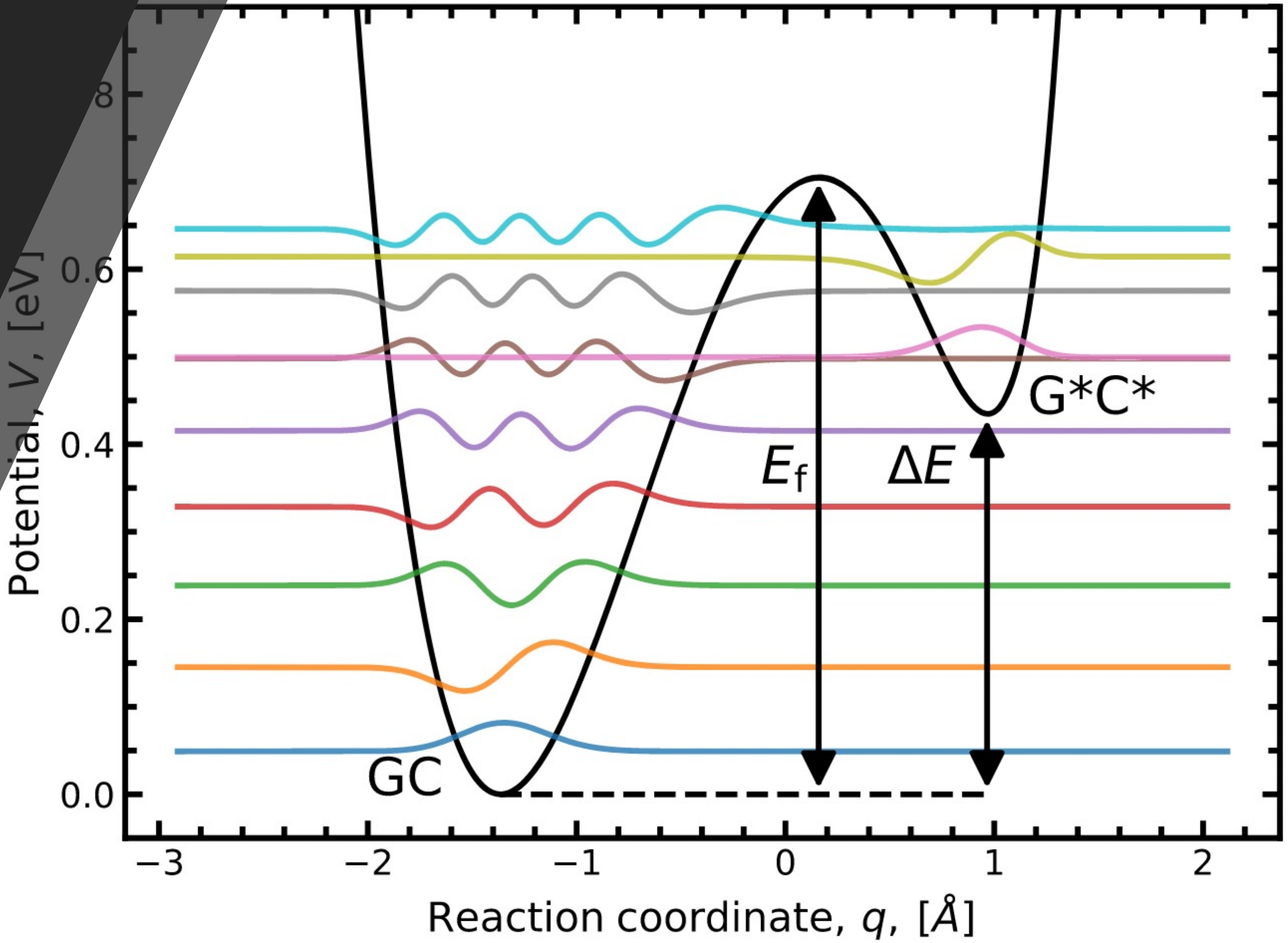
Scanning Tunnelling Microscope

- Commonly used to image objects at the atomic level
- A nanometer thin tip is scanned above the surface of the object
- A voltage difference is created between the tip and material
- Vacuum between the tip and object acts as a potential barrier



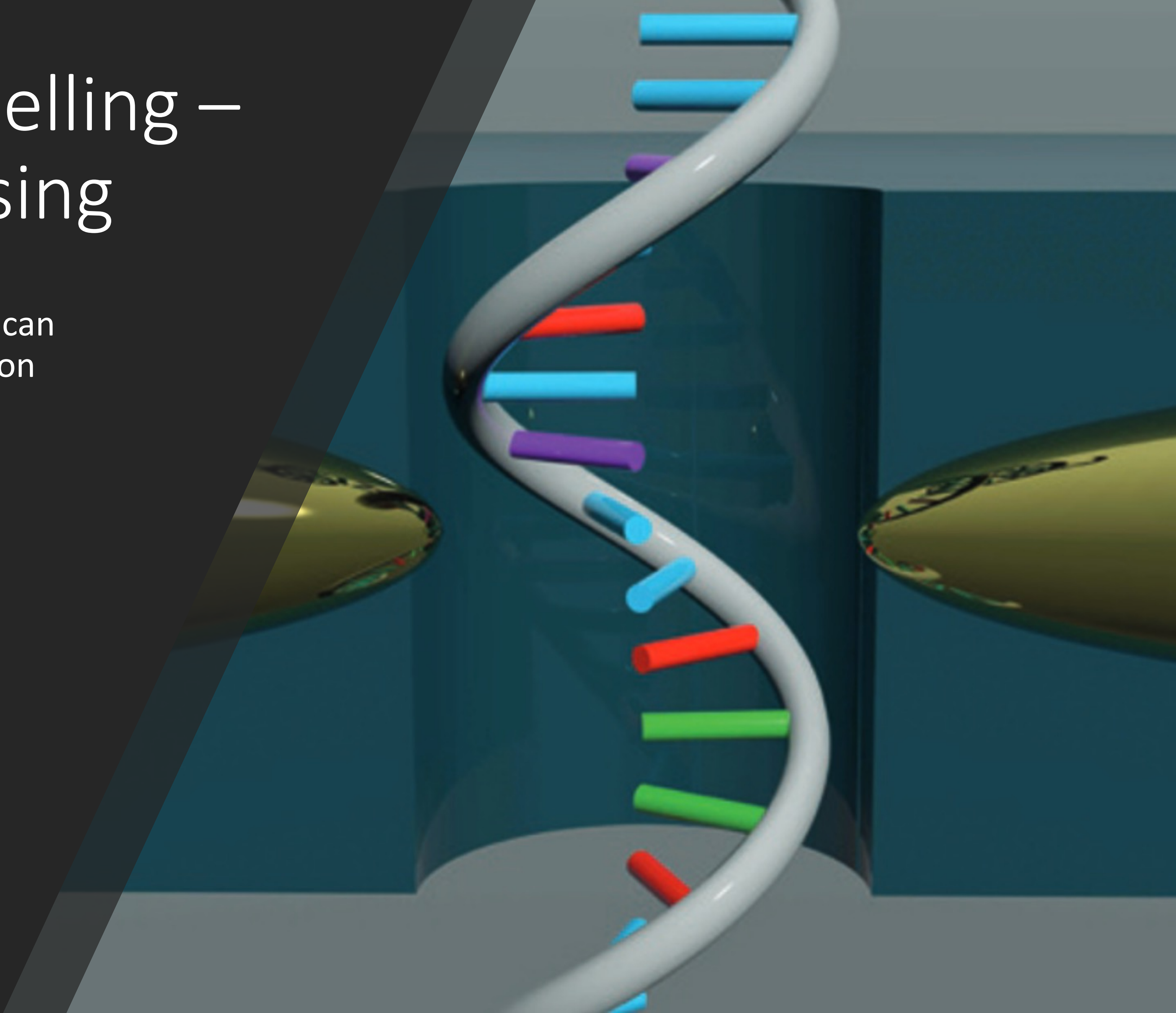
Quantum Tunnelling – Molecular Sensing

- Quantum particles can tunnel through lines of DNA
- The probability of tunnelling can be used to learn about the barrier itself
- This barrier modelling a proton passing through a molecule



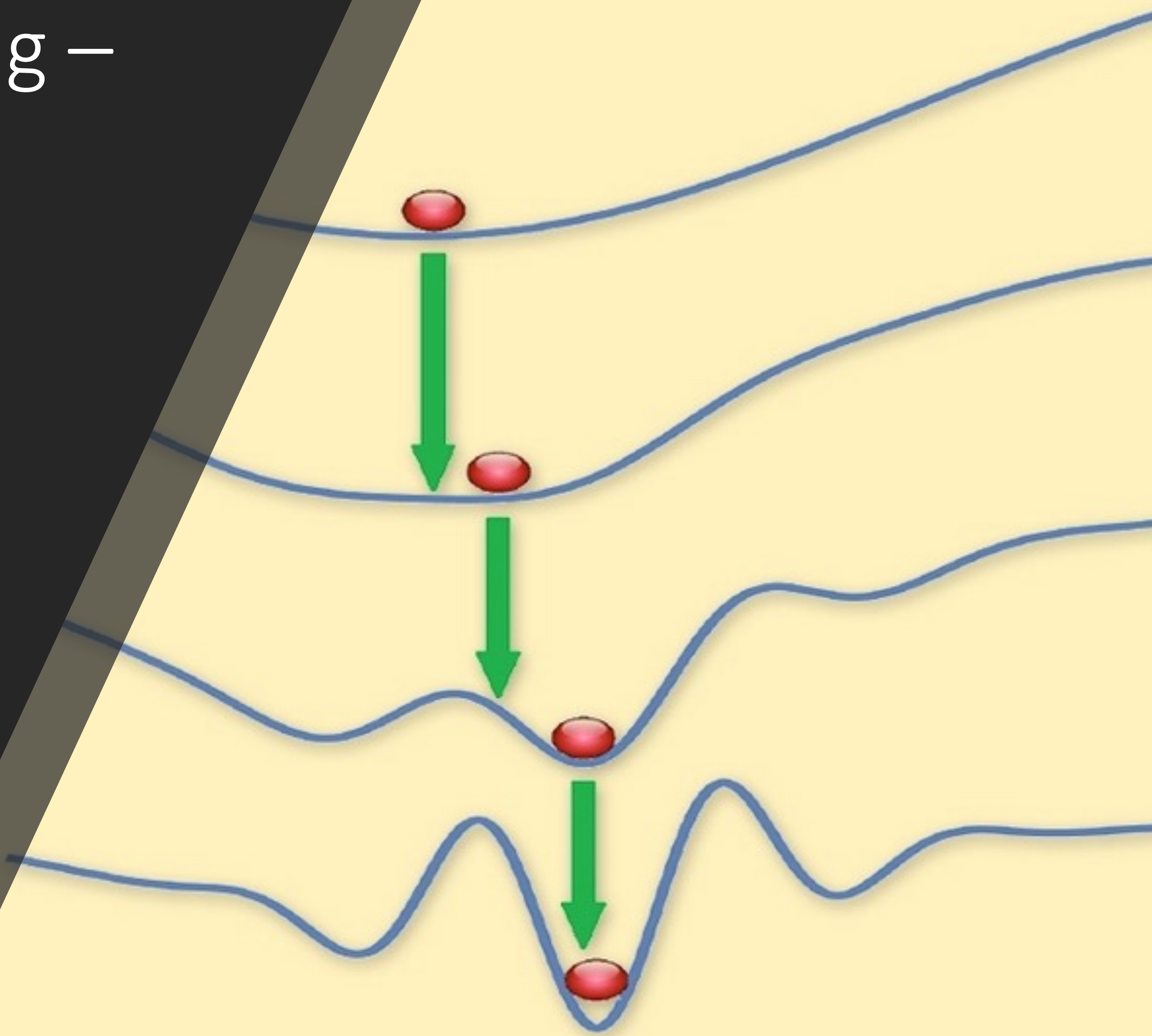
Quantum Tunnelling – Molecular Sensing

- Quantum Tunnelling scanners can be used to read a DNA strand on a molecular level



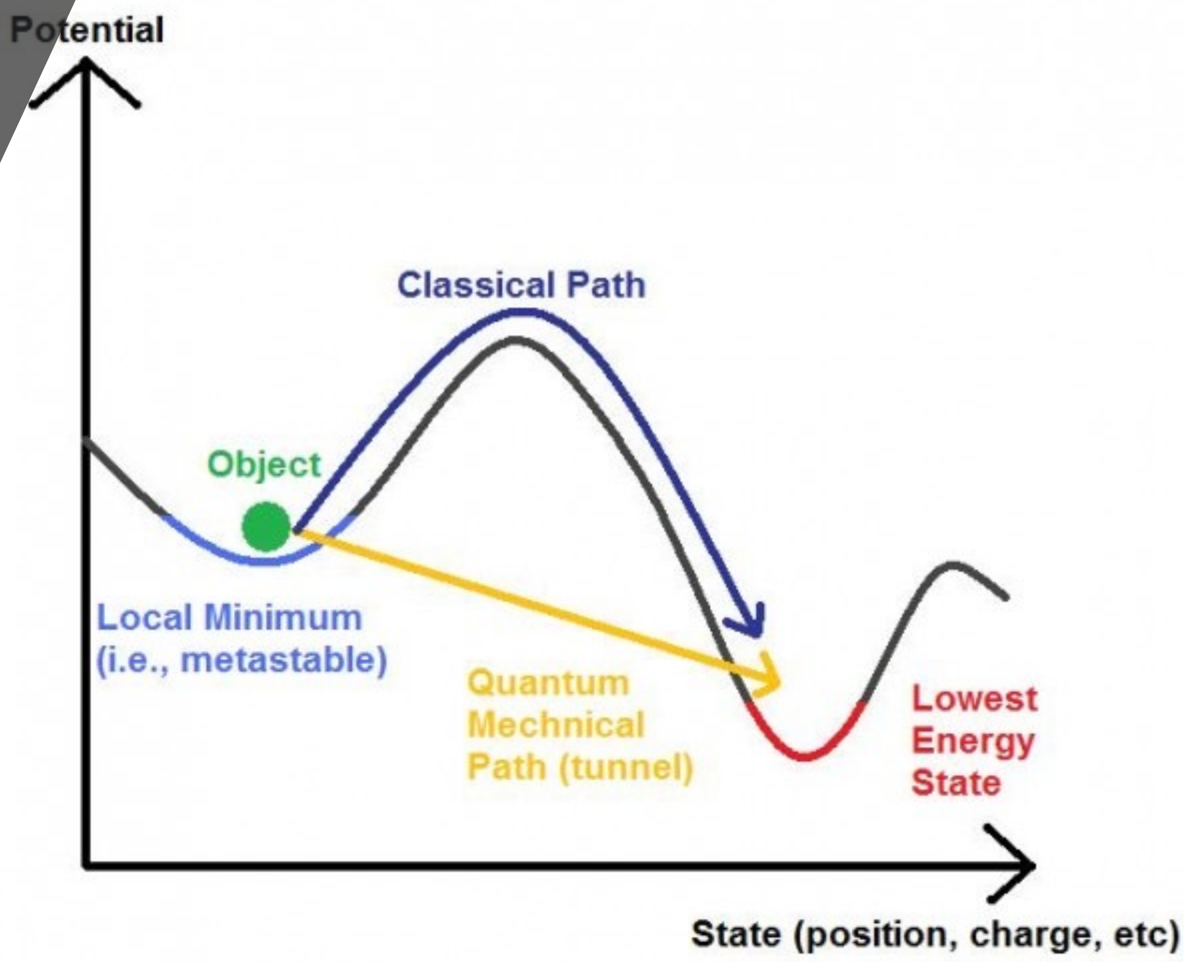
Classical Computing – Optimization

- Almost every problem computers solve involves optimization
- Every problem in machine learning and AI uses optimization
- A common problem in finding the 'minimum' is local dips
- Many simple algorithms will become trapped in local minima instead of finding the true minimum



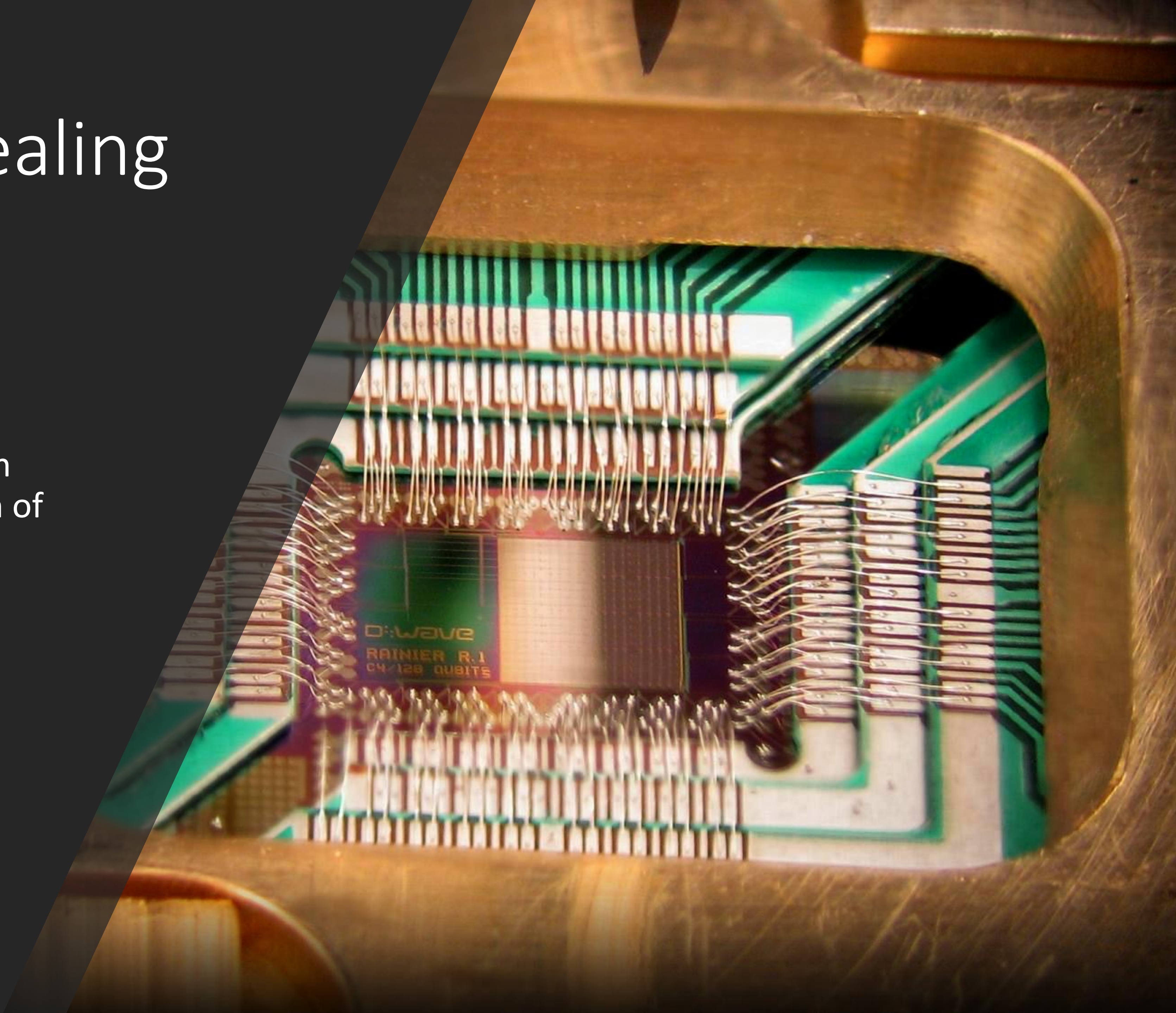
Quantum Tunnelling – Optimization

- Quantum tunnelling allows particles to pass through energy barriers
- An optimization technique attempts to reach the 'lowest energy state'
- Optimization can be solved by placing a quantum particle in a potential that matches the optimization function



Quantum Annealing

- In Vancouver, one company is already commercializing a quantum annealing device
- D-Wave leverages tunnelling in optimization with the addition of *quantum superposition*



What other problems would benefit from quantum tunnelling?