Quantum:
Wave-Particle Duality

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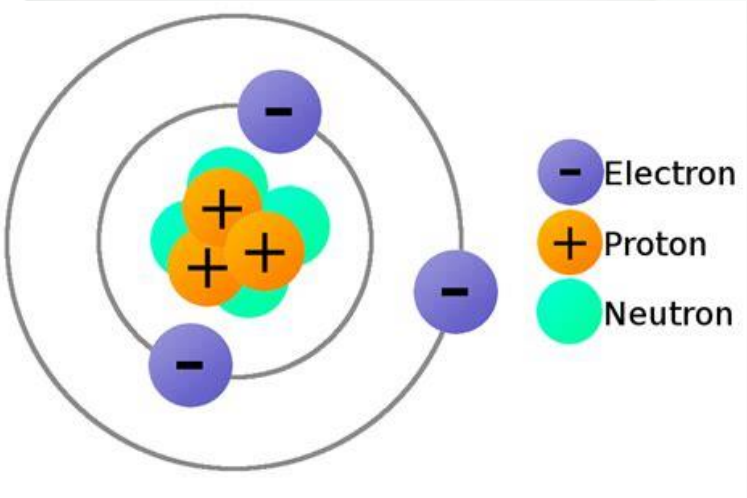
What is an electron?



Definition of *electron*

: an elementary particle consisting of a charge of negative electricity equal to about 1.602×10^{-19} coulomb and having a mass when at rest of about 9.109×10^{-31} kilogram or about $^{1}/_{1836}$ that of a proton

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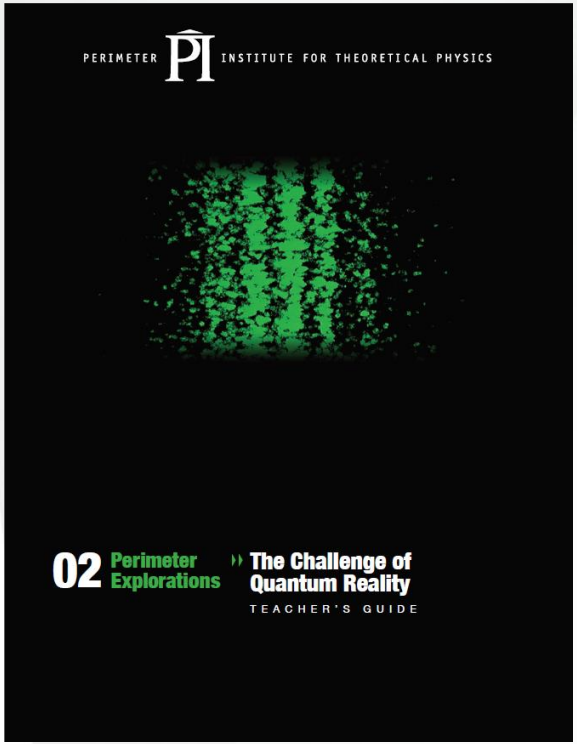
The Challenge of Quantum Reality



Activity 4: Investigating the Nature of the Electron

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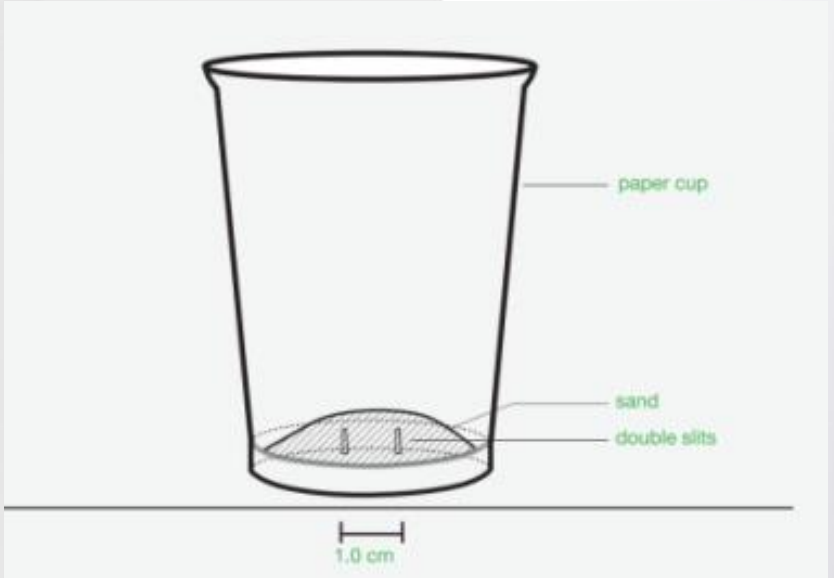
Double-slit Experiment with **Classical Particles**

1. **Predict** what pattern the salt will make on the paper.

2. **Explain** your prediction.



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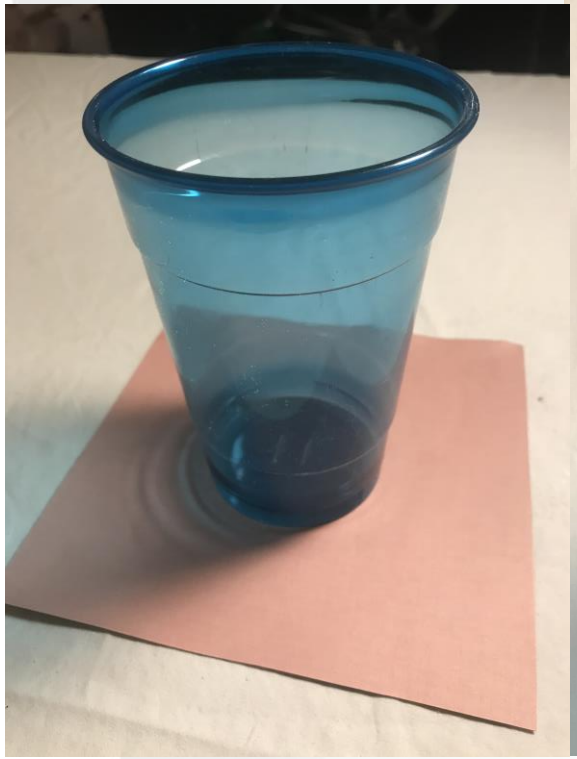
Double-slit Experiment with **Classical Particles**



Double-Slit with Classical Particles

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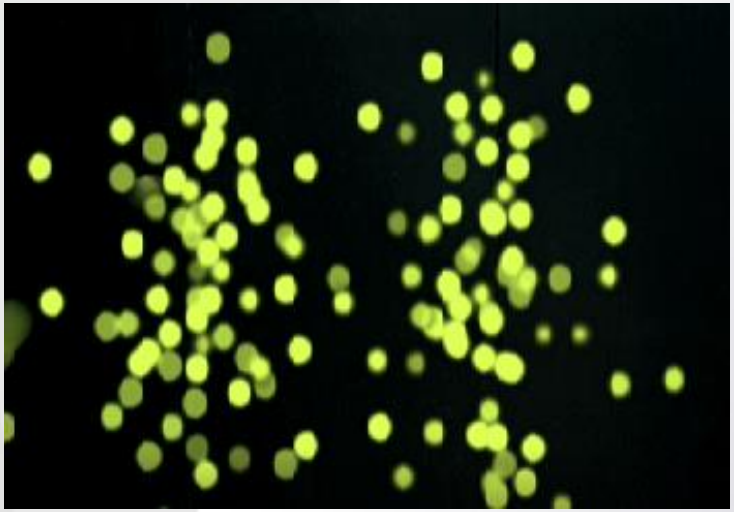
Key properties of classical particles

1. Localized
2. Collide with each other
3. Don’t interfere with each other



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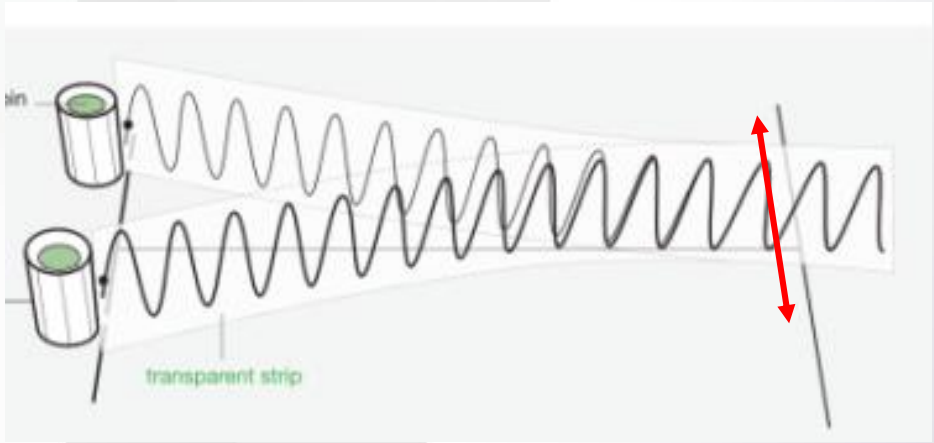
Double-Slit Experiment with Classical Waves

1. **Predict** what pattern the waves will make along the line.
2. **Explain** your prediction.



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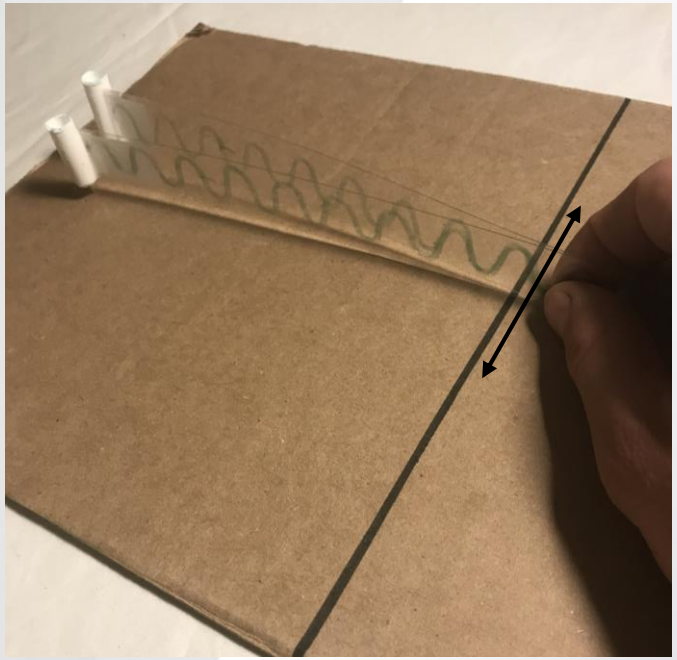
Double-slit Experiment with **Classical Waves**



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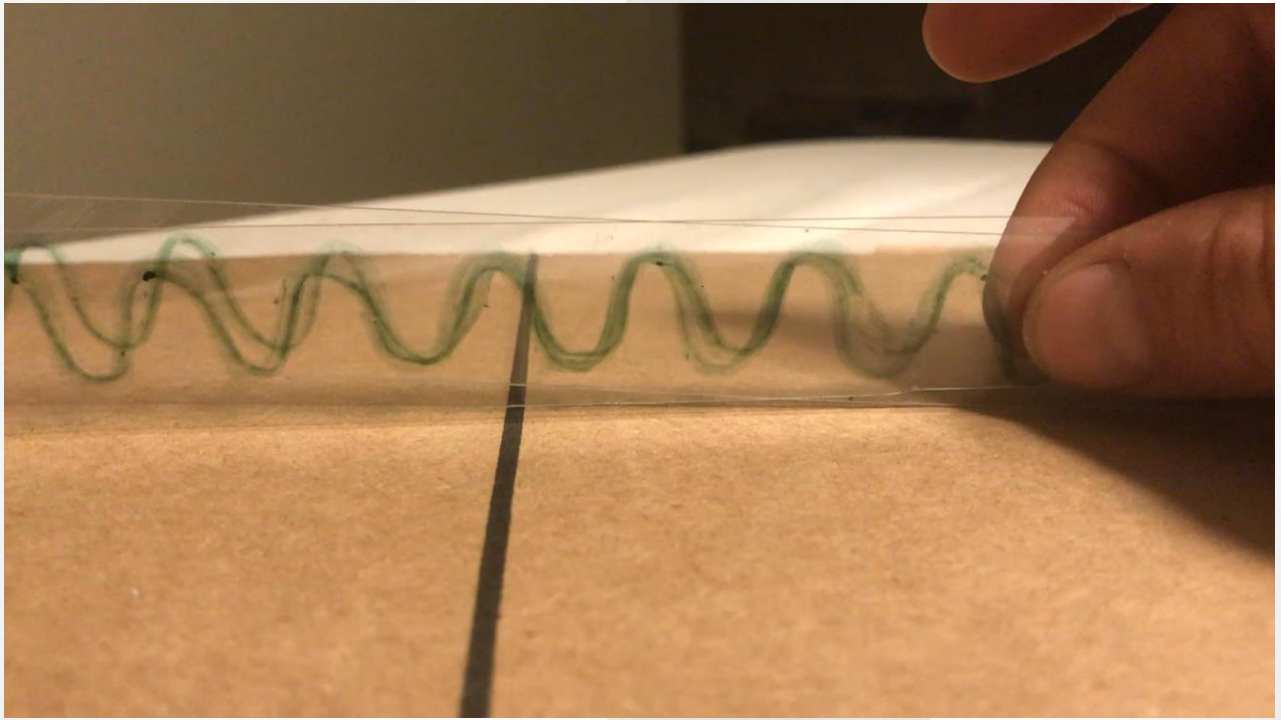
Double Slit with Classical Waves



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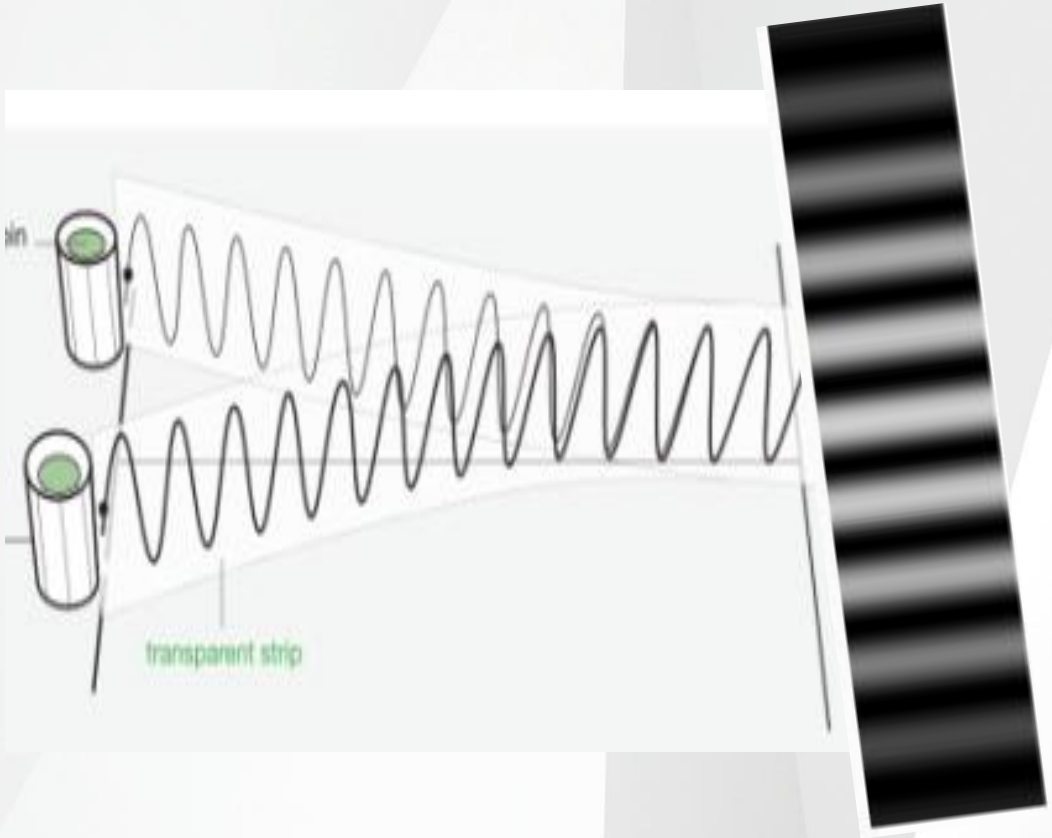
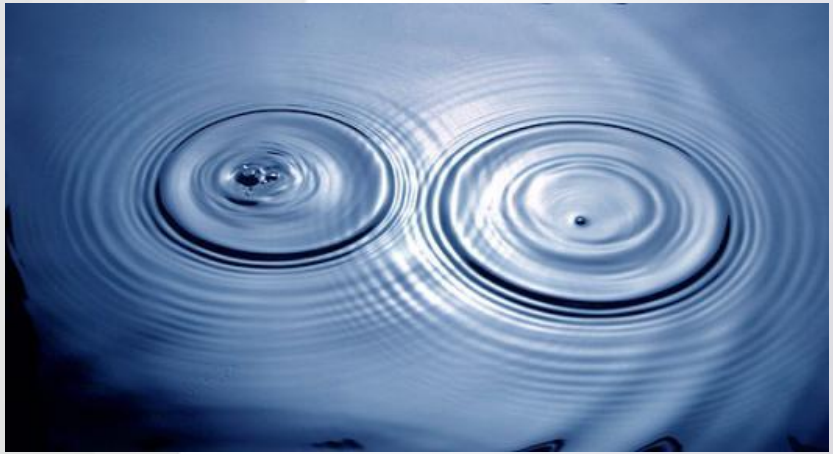


Key properties of classical waves

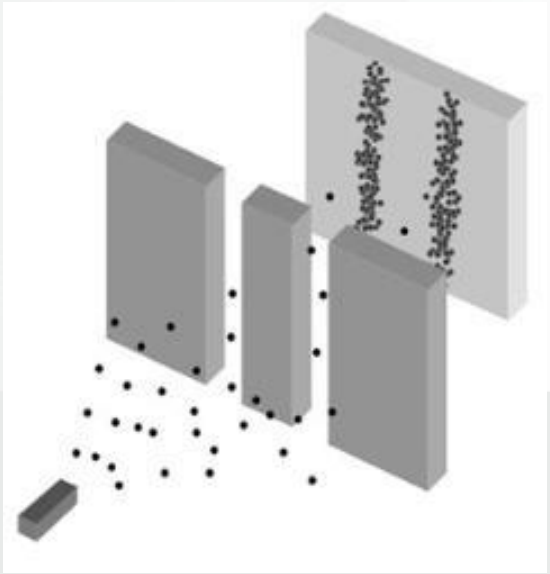
1. Spread out (non-localized)
2. Interference (constructive & destructive)
3. Don’t collide with other waves



Summary

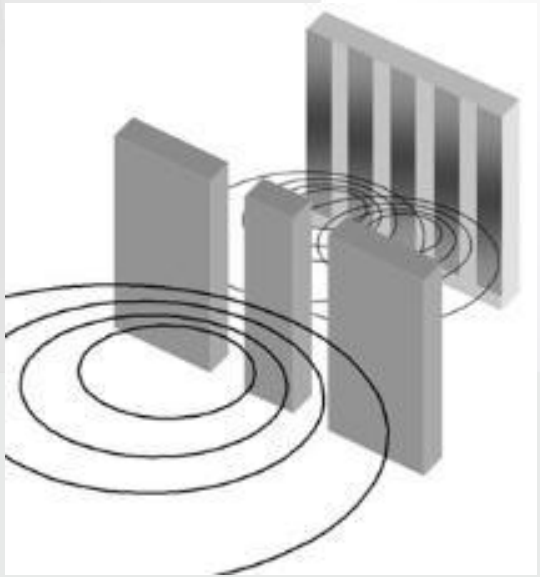
CLASSICAL PARTICLES

1. Localized
2. Collide with each other
3. Don't interfere with each other



CLASSICAL WAVES

1. Spread out (non-localized)
2. Interference
3. Don't collide with other waves



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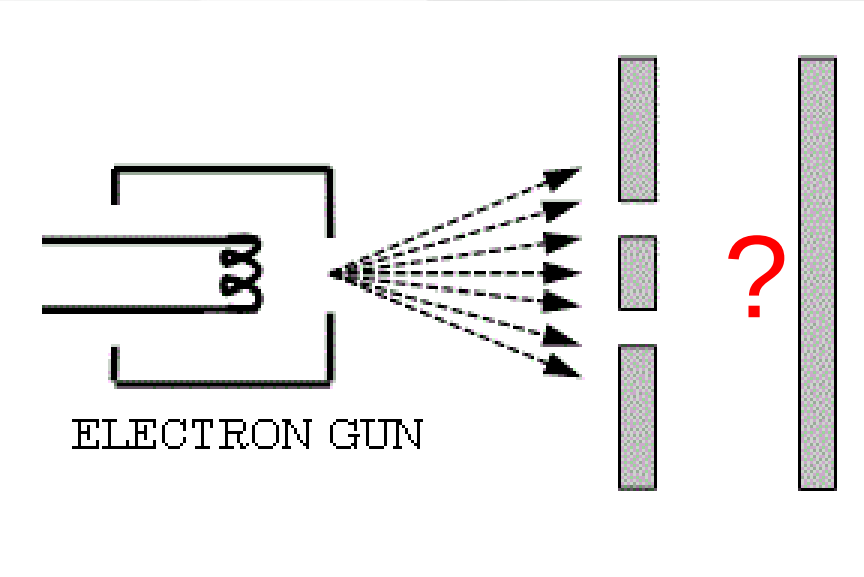
What happens when electrons go through the slits?



What pattern do we observe?

Double Slit with Electrons

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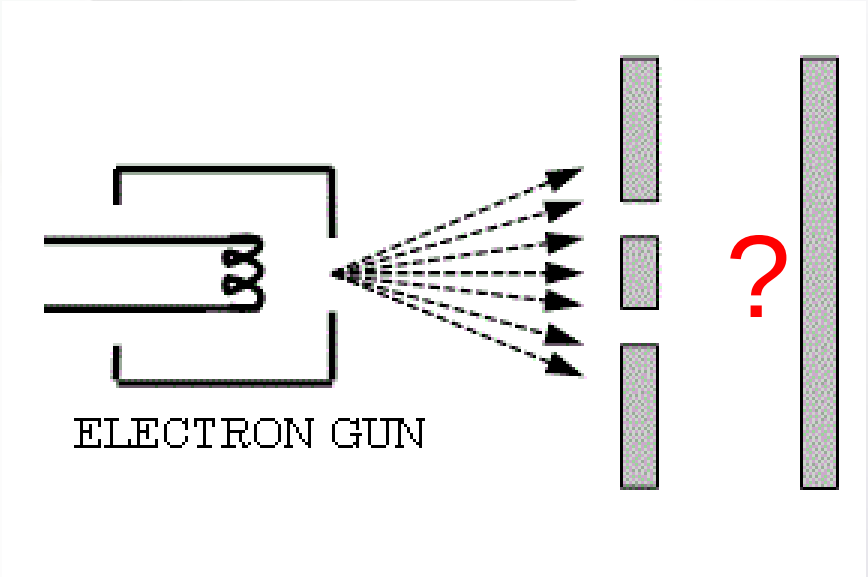
Electron Double-slit Experiment

Predict what pattern is observed on the detection screen. **Explain** your prediction.



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Observation

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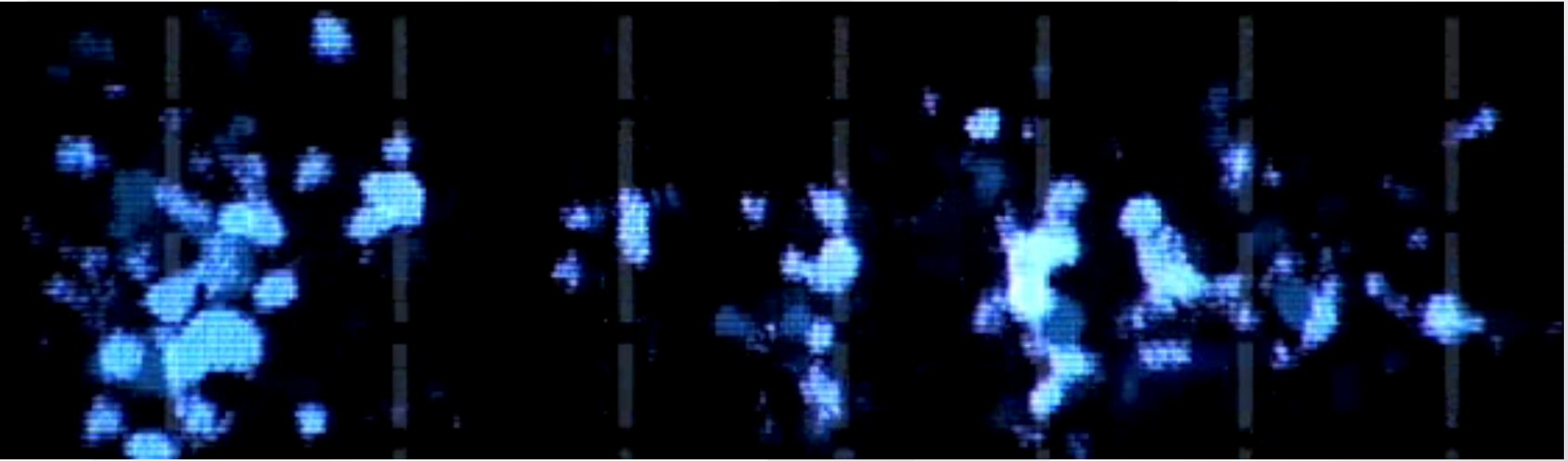
Observation



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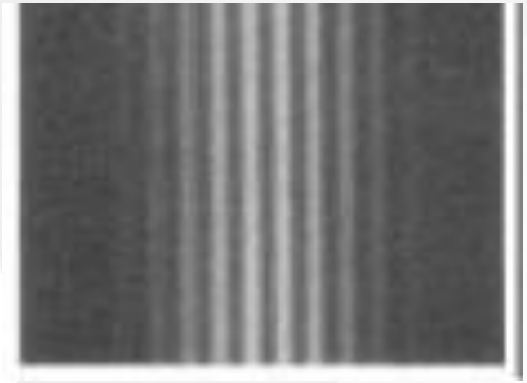
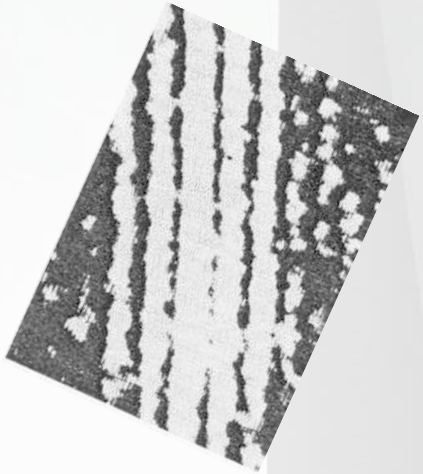
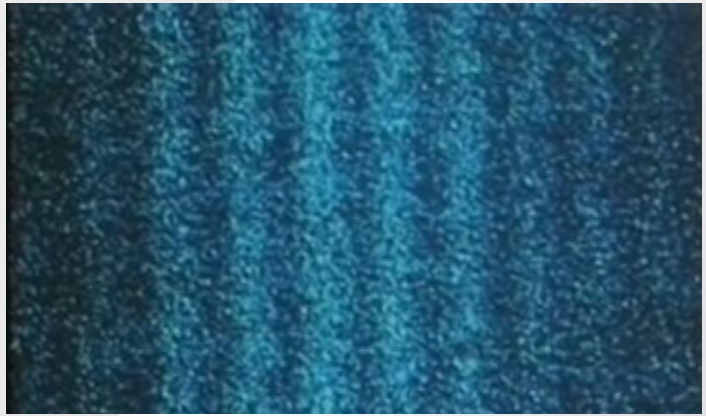
Many other experiments have observed similar results



Jönsson 1961



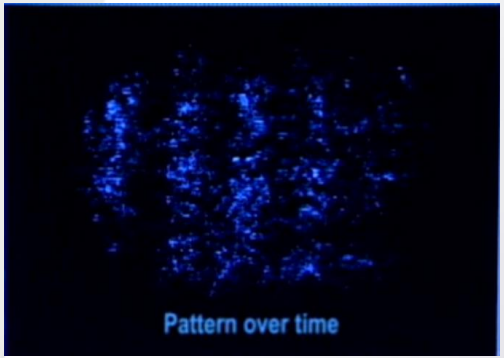
Merli et al. 1976



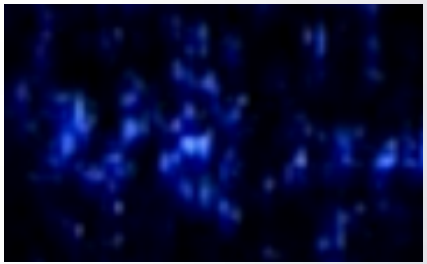
Tonomura et al. 1989

Wave-Particle Duality

- **Wave model** explains overall pattern



- **Particle model** explains each individual election detection.



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Research shows that students cling tenaciously to their "incorrect" beliefs

Eugenia Etkina,
Physics Education Researcher
Rutgers University

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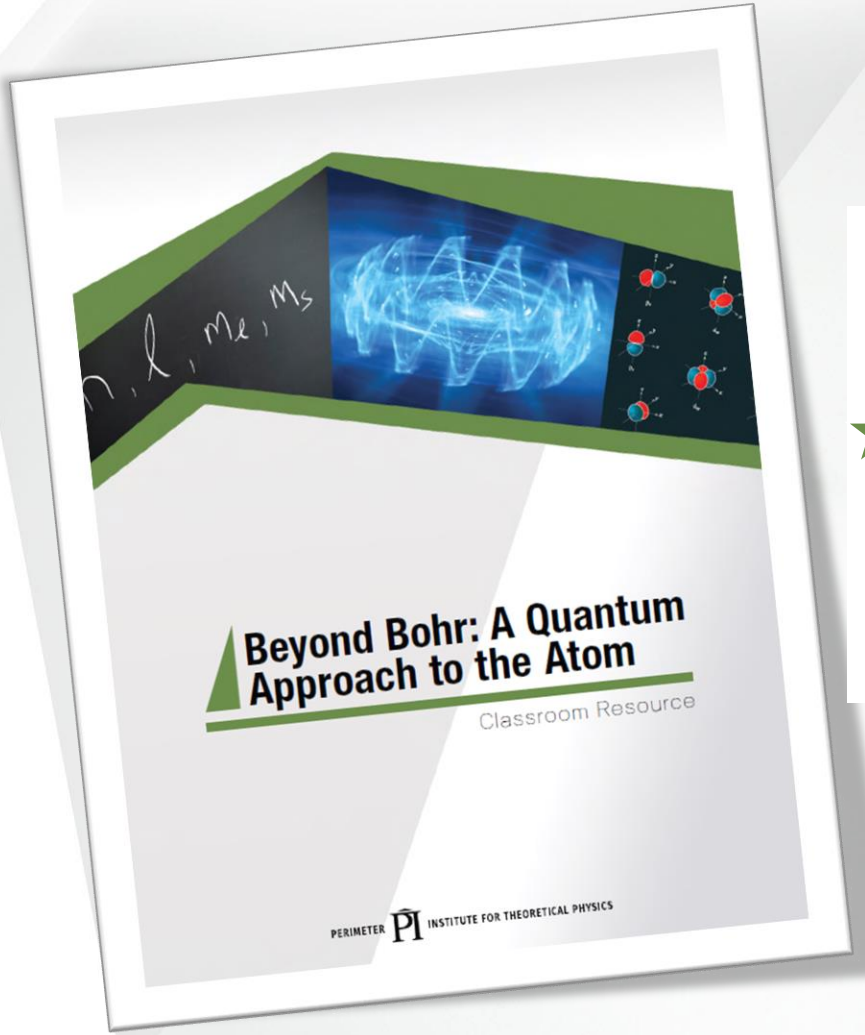

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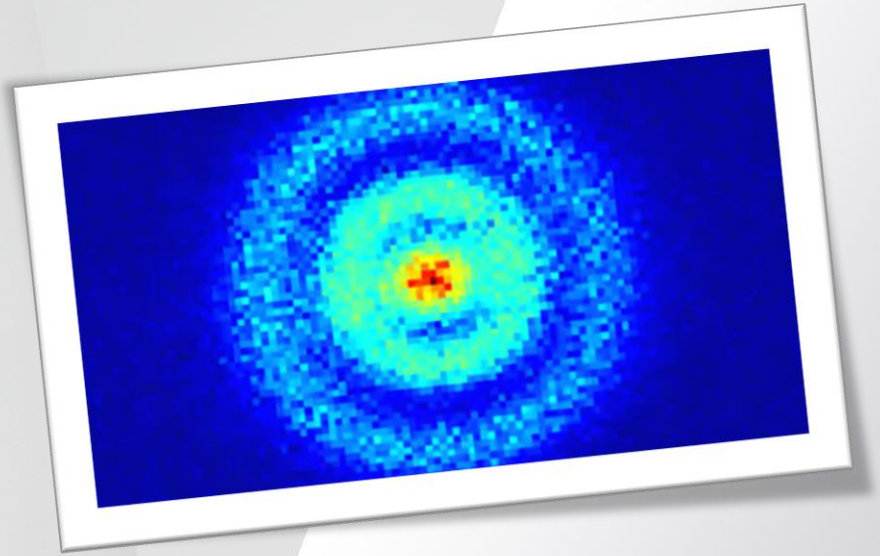
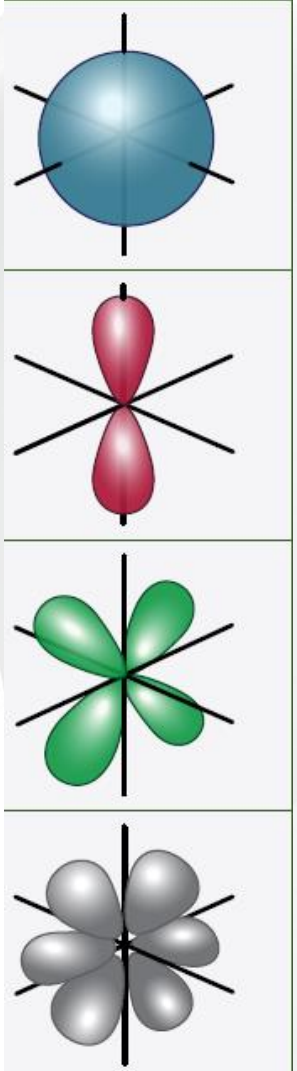
Application Orbitals

Image made by detecting the locations of the electron in thousands of hydrogen atoms.

The shapes represent different probabilities of detecting the electron.

Scientists call the shape an *orbital*.

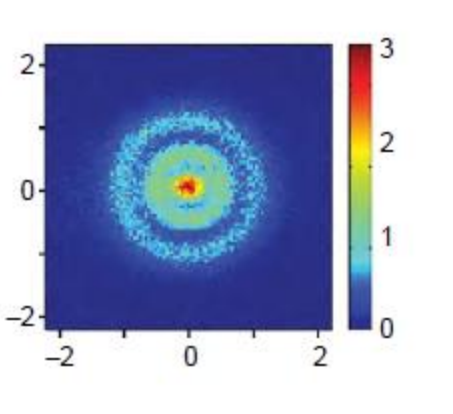




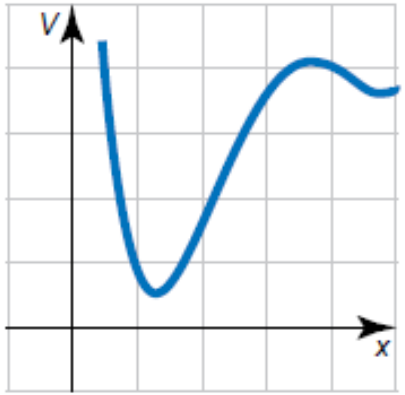
Application: Orbitals

- Orbitals are:
  - regions where the probability of detecting an electron is high
  - described by wave functions
  - a consequence of the wave-like properties of electrons

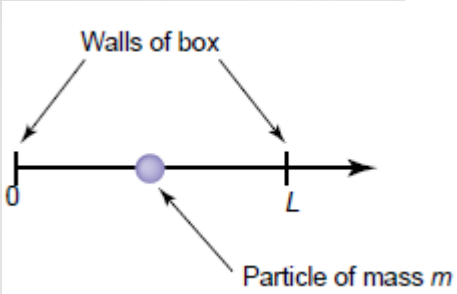
Electrons in Atoms are Bound (constrained)



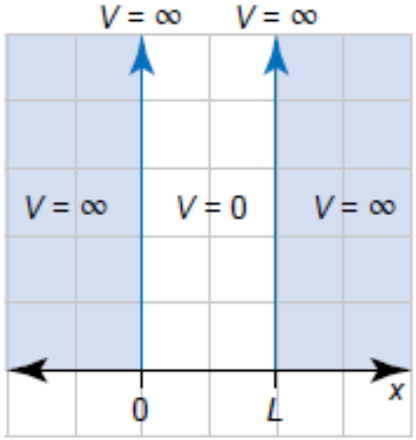
Atom



simplify



1-D box



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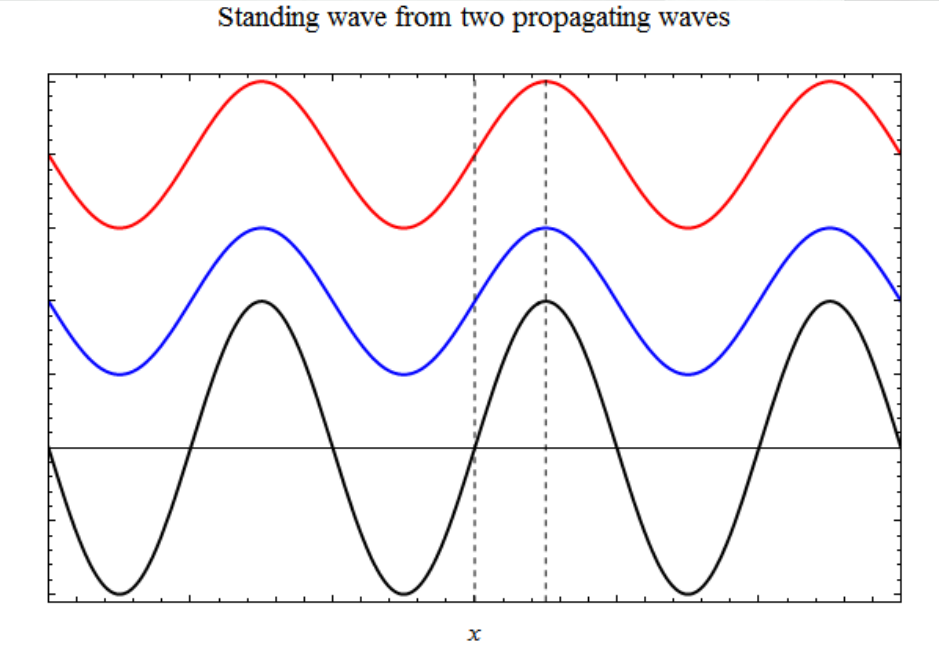
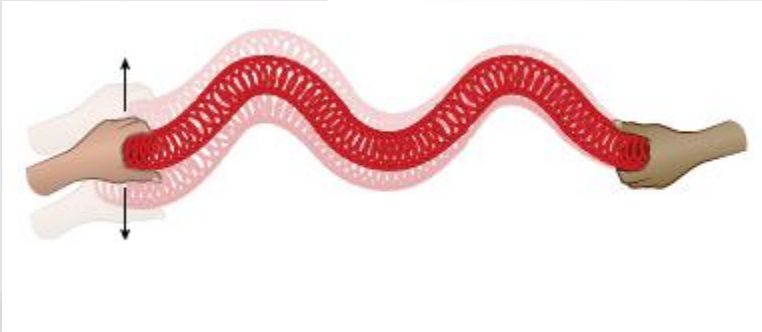
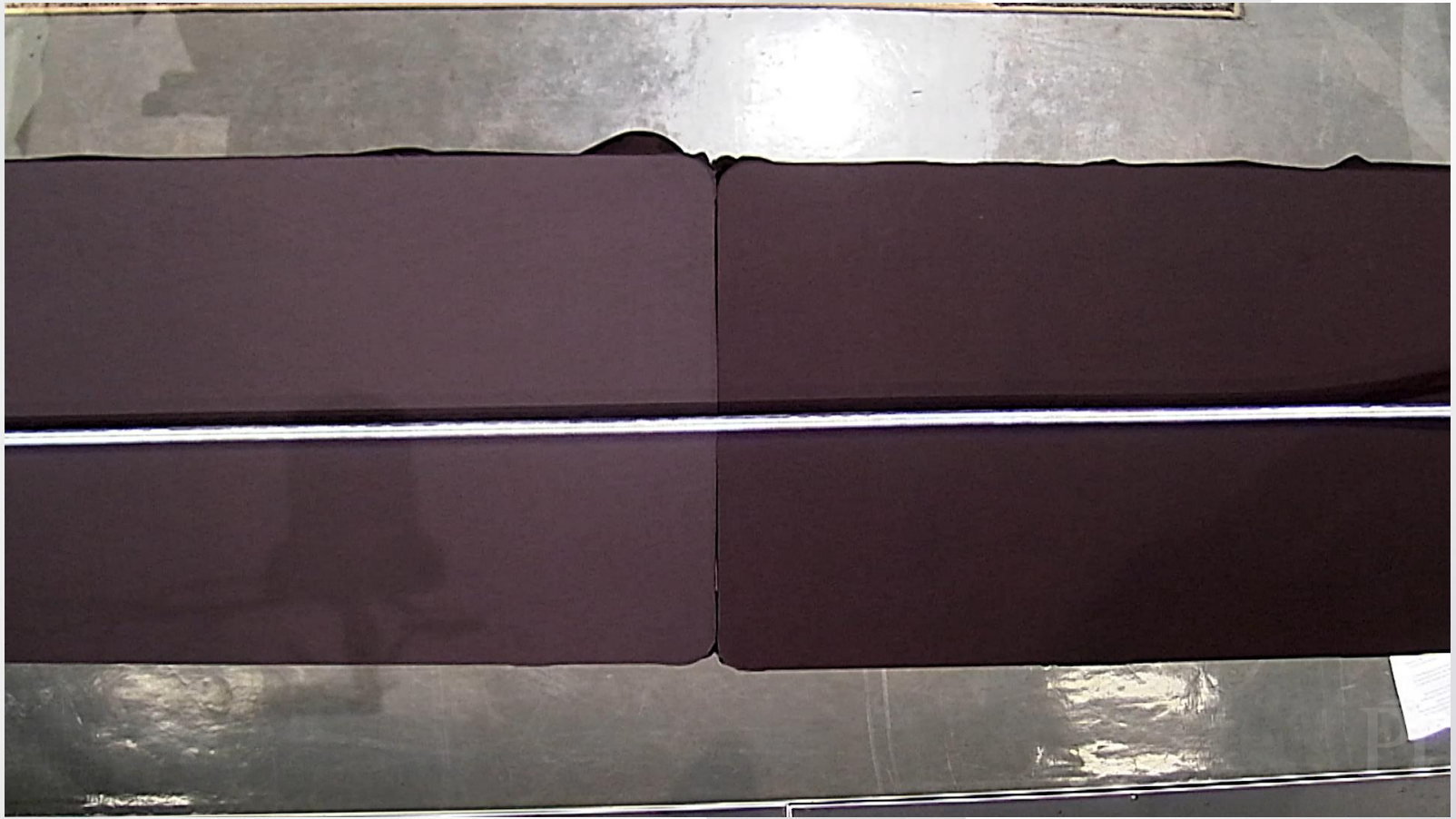
Waves in a Box







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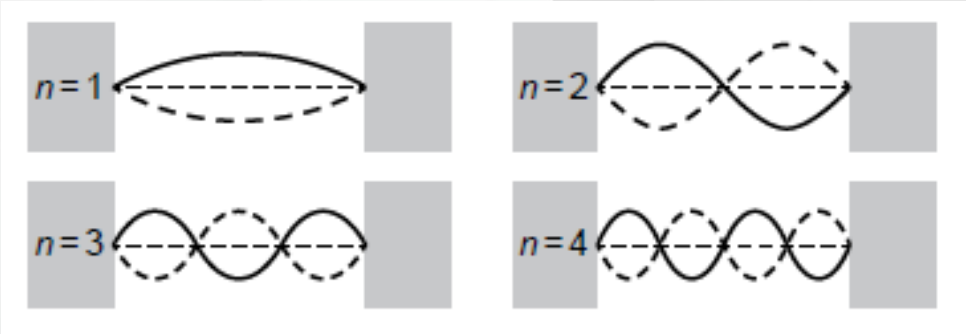
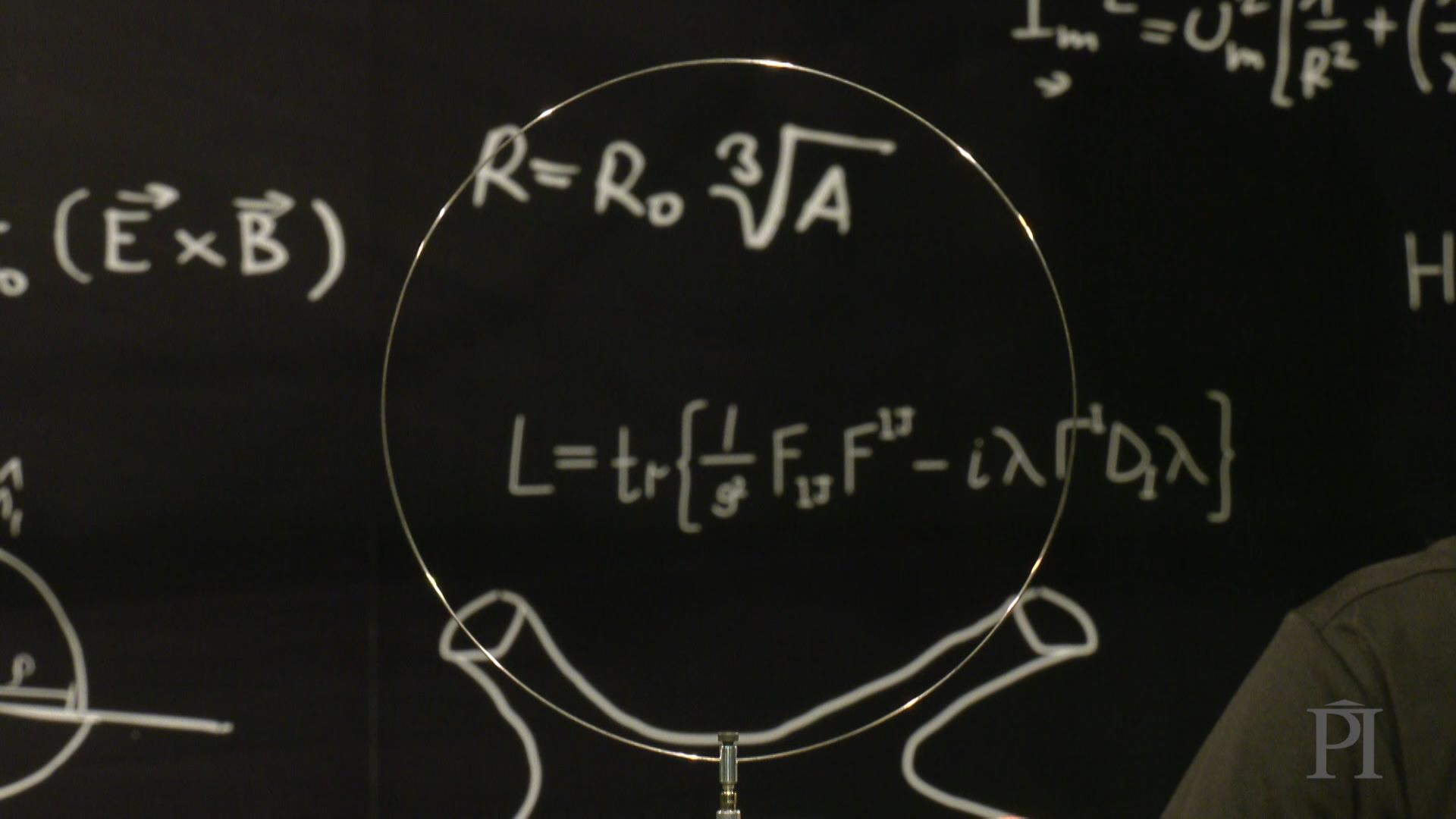
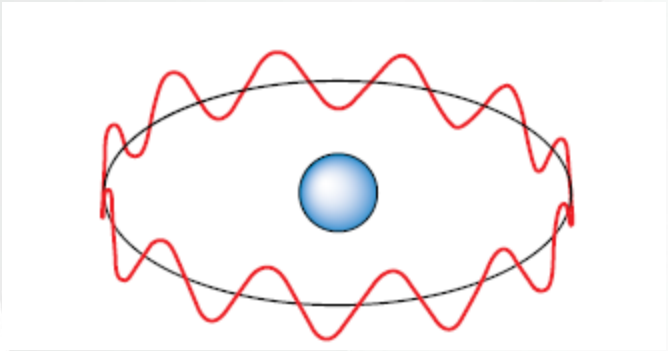
Stable configurations of Waves in a Box

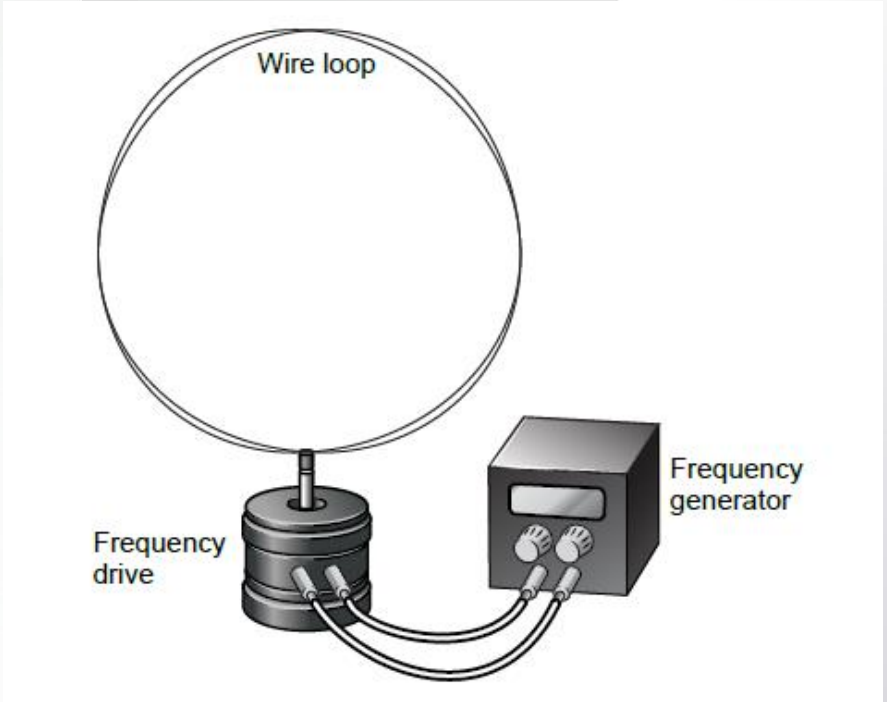


$$\lambda = \frac{2L}{n}$$

Wire Loop Demo


$R = R_0 \sqrt[3]{A}$
$L = tr\left\{\frac{1}{g^2} F_{\mu\nu} F^{\mu\nu} - i\lambda \Gamma^{\mu} D_{\mu} \lambda\right\}$





Is the electron *actually* a wave?

- What would happen to charge if it were spread out like a wave?
- Waves can be partially reflected and transmitted. Is this true for electrons?
- What would you expect to see on the screen for a single electron wave striking the screen?

Electrons defy our classical models.

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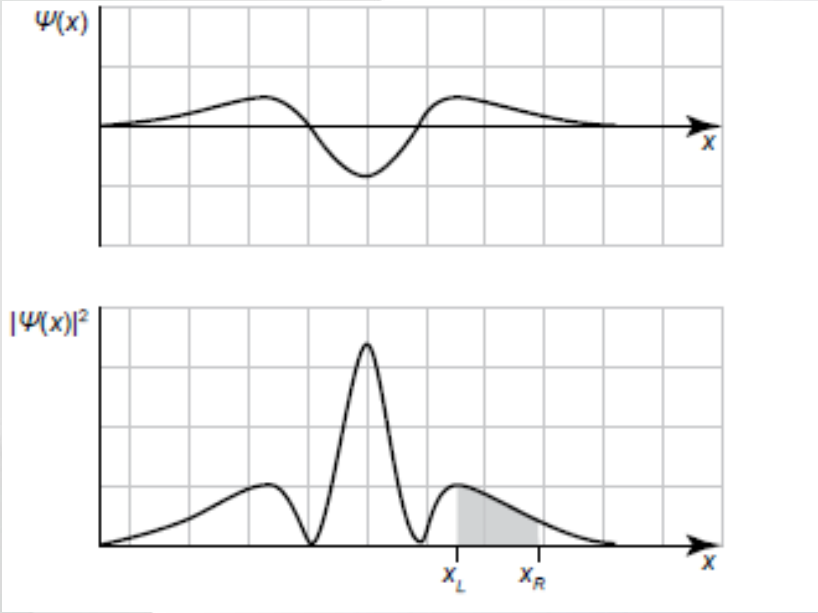
Wave Functions

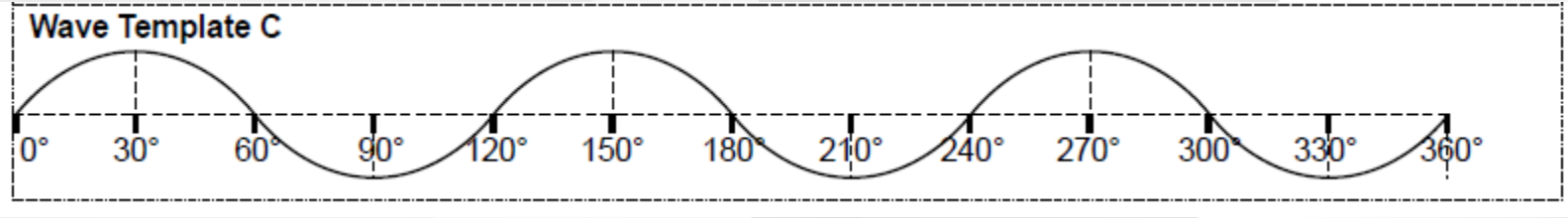
Activity 1

- Use the mathematics of waves to describe electron behaviour
- Probability of detecting the electron as a particle
- Progression from de Broglie



Wave Template

ψ



✓ Mark locations where the probability of detecting an electron is highest

✗ Mark locations where the probability of detecting an electron is lowest

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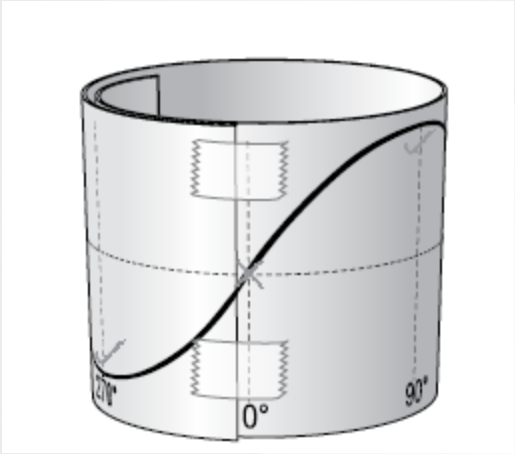
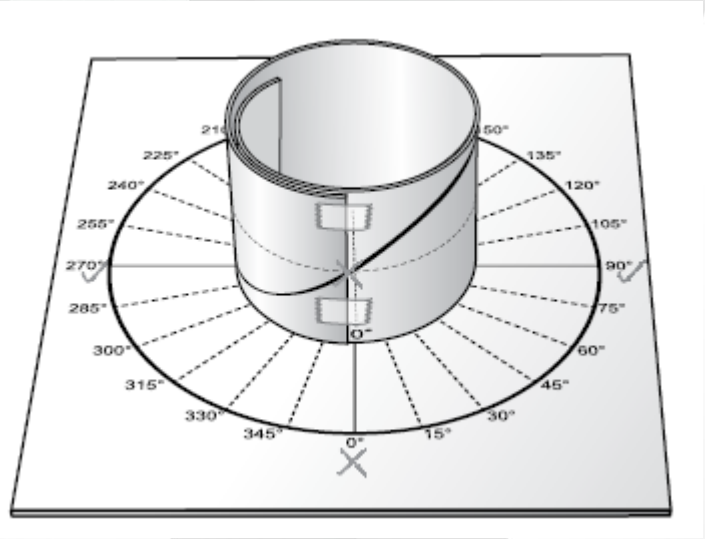
Line up on Circular Graph





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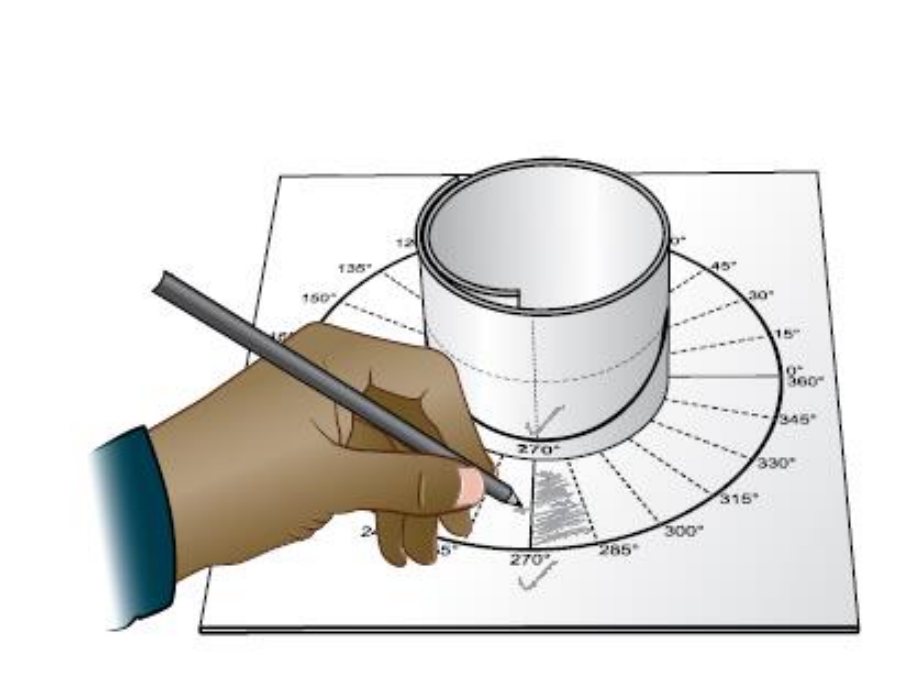
Shade in the Zones



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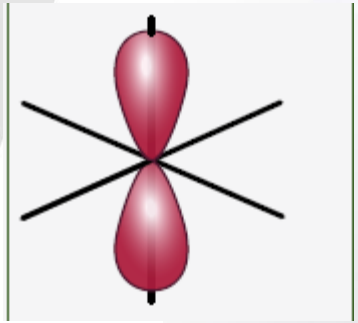

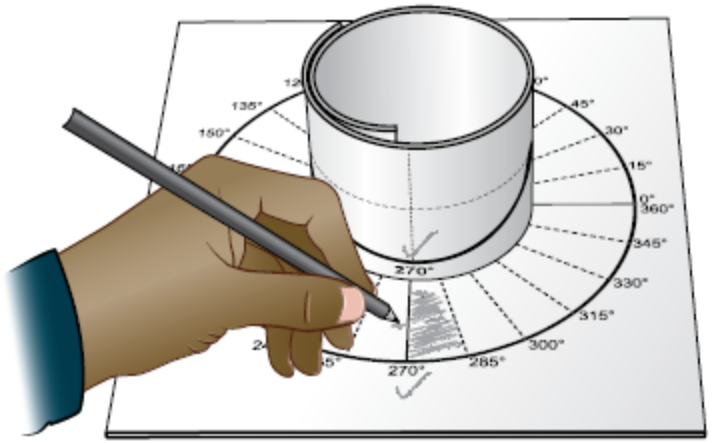

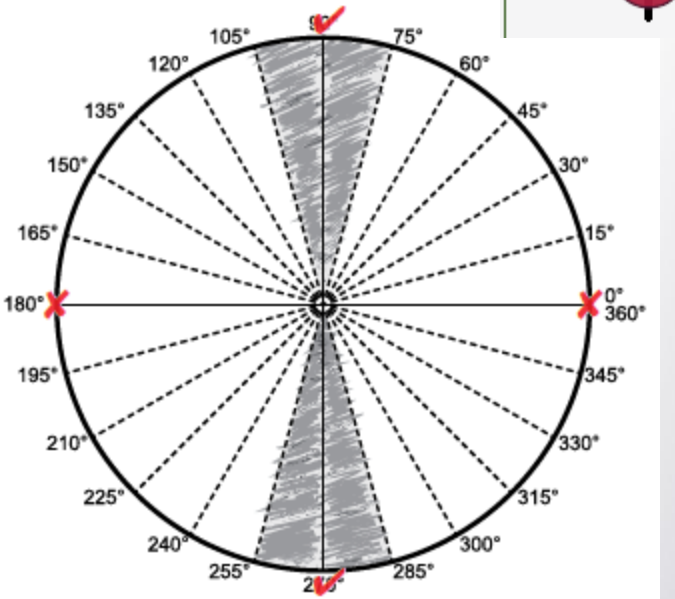

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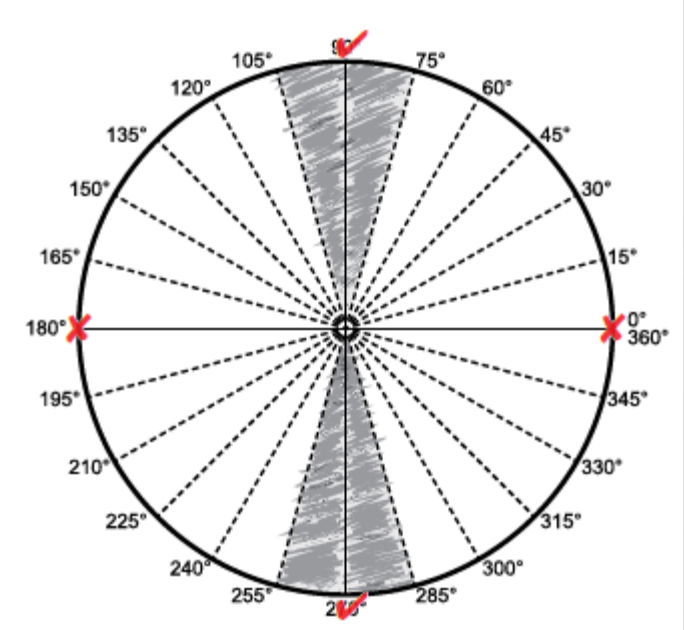
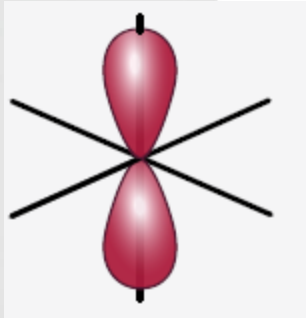
p orbital





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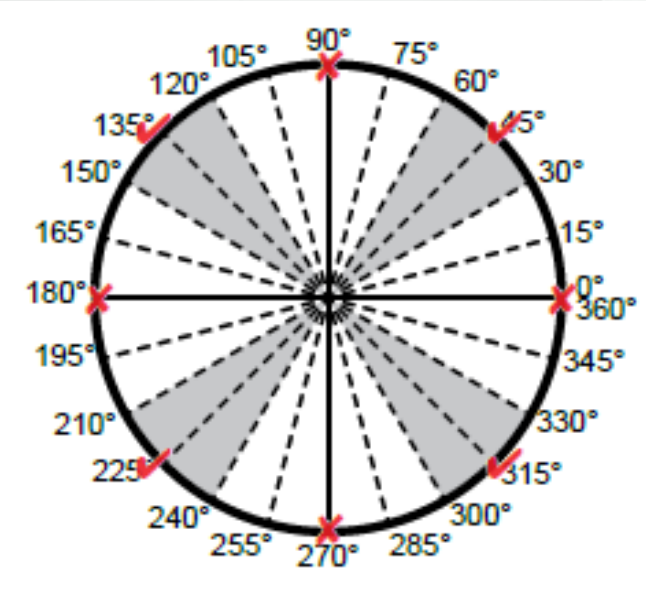
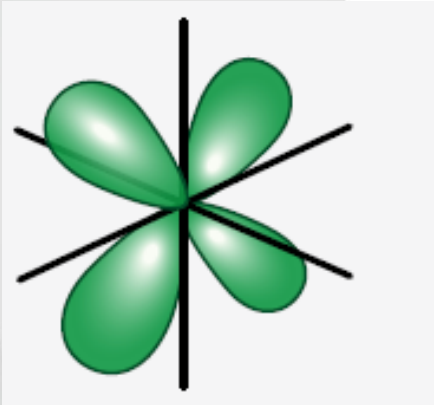
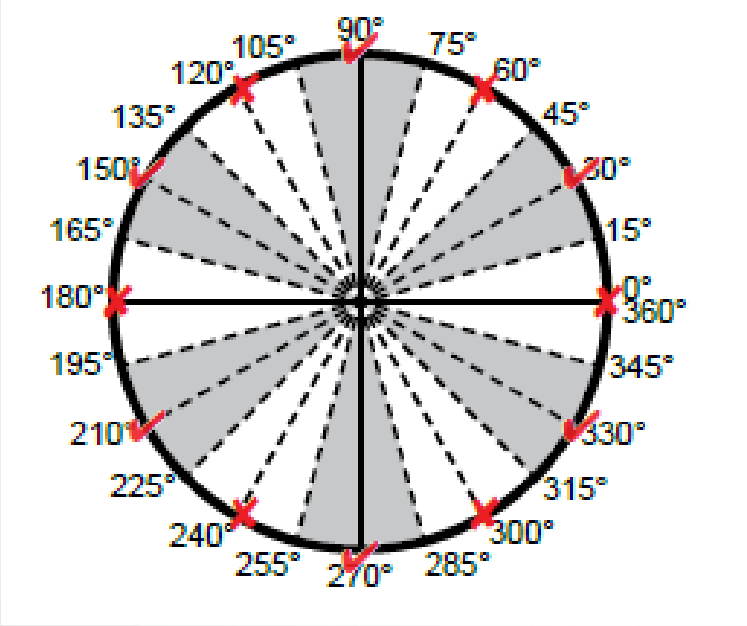
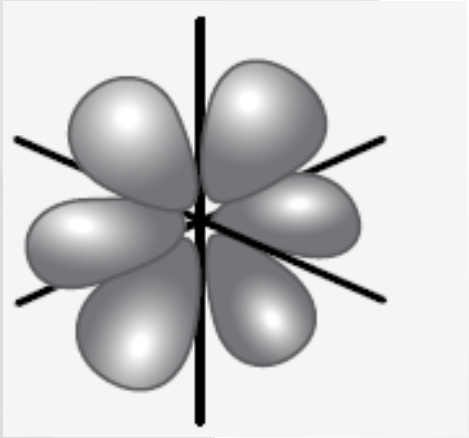
d orbital



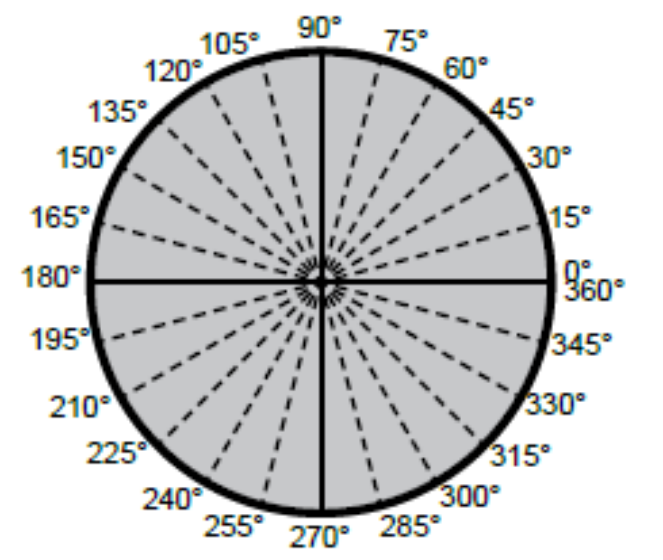


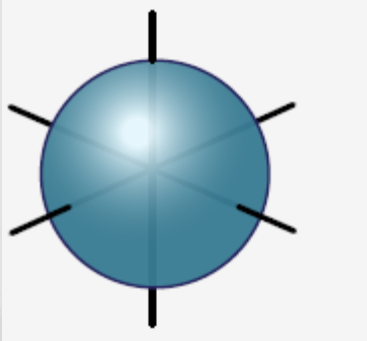
f orbital





s orbital

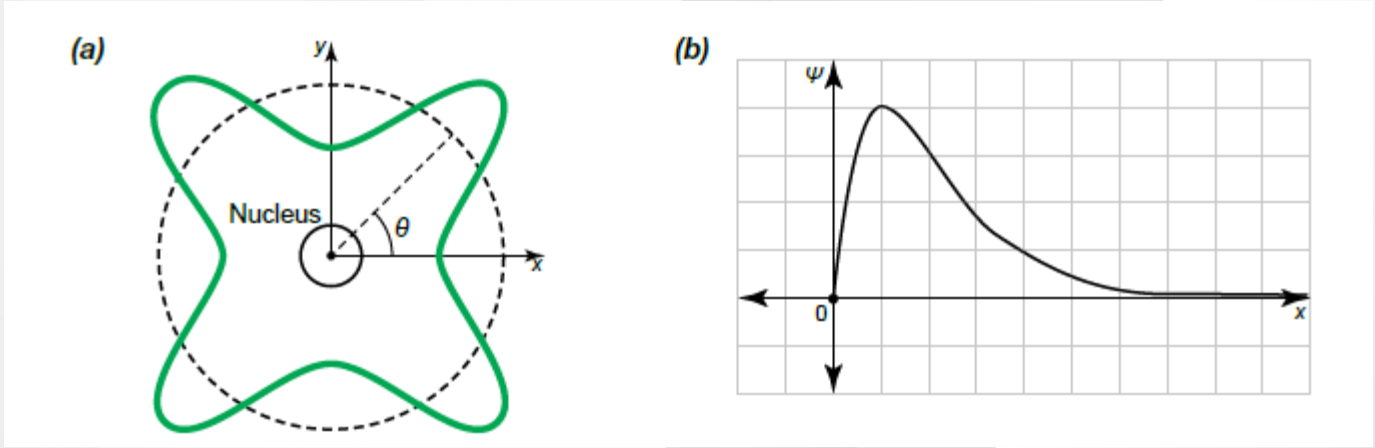




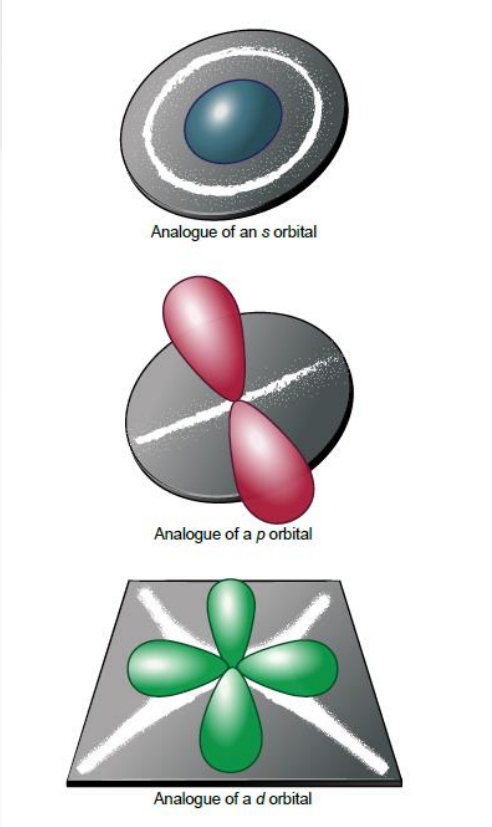
Orbitals are 3D

Angular

Radial



Extension: Chladni Plates



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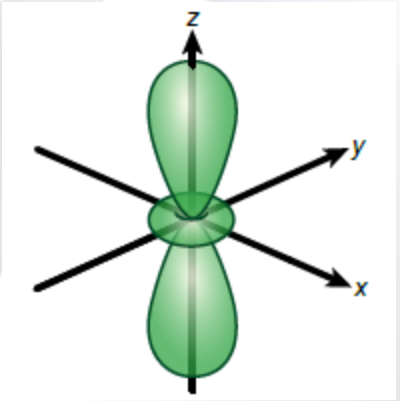
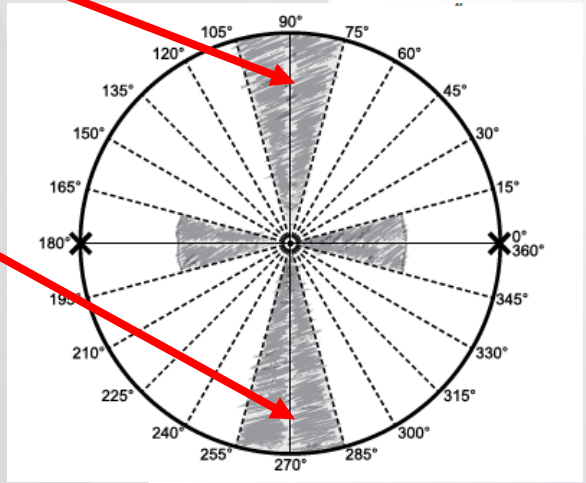
Doughnut Shape of d_z^2

Sinusoidal shape that is shifted up





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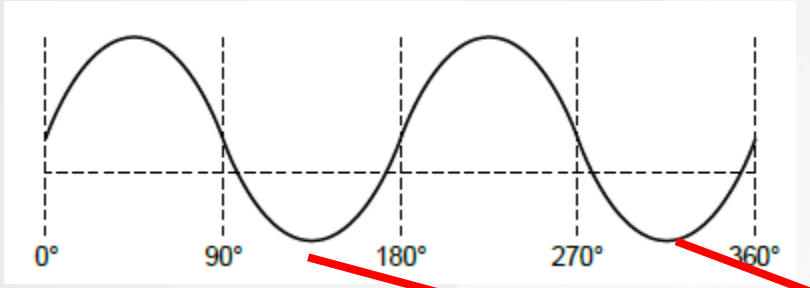
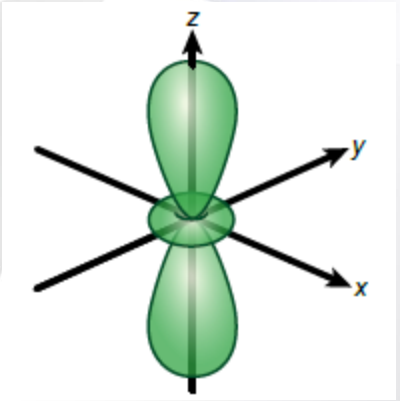
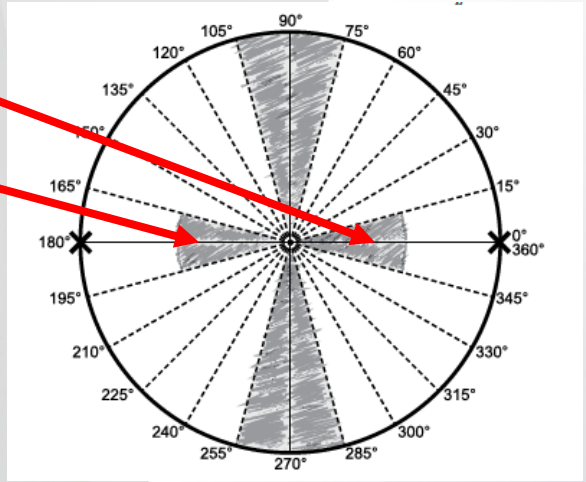
Doughnut Shape of d_z^2



Sinusoidal shape that is shifted up





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