Improving Conceptual Understanding Through Visual Learning

An Example from Quantum Mechanics

Gina Passante, California State University Fullerton

CALIFORNIA STATE UNIVERSITY
FULLERTON

Antje Kohnle
St Andrews University

CALIFORNIA STATE UNIVERSITY FULLERTON

- Part of the California State University (CSU) system
- Physics has BS and MS degrees
- Hispanic-serving institution
  - (42% Hispanic/Latinx, 20% White)
- 40,000 students (57% female) {physics 25% female}
- 47% of Physics BS were ‘first generation’ (last 10 yrs)

https://www.parishcaptains.com/morro-bay-map-california/morro-bay-map-california-map-beaches-in-southern-california-valid-united-states-map-i-can/

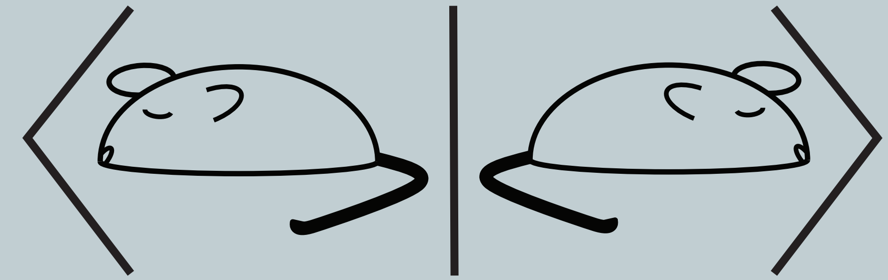
PER @ California State University Fullerton

Faculty
Michael Loverude
Gina Passante

Postdoc
Benjamin Schermerhorn

Masters Students: Mikayla Mays, Anthony Arruda, Zong Yu Wang, Adam Quaal
Undergraduate Students: Anthony Pina, Anderson Fung, Courtney White, Miguel Ramirez, Pachi Her, Kyle Vu, Regan Jones, Thanhnhan Phan, Sean Young

Research as a base to develop adaptable curricula bridging instructional paradigms in quantum mechanics



Homeyra Sadaghiani
Steven Pollock

physport.org/curricula/ACEQM

DUE-1626594

Student learning in Quantum Mechanics

Student thinking about measurements across the physics curriculum

Natasha Holmes

DUE-1809178

Visual Learning in QM: Developing Simulation-Tutorials

Antje Kohnle
(Shaaron Ainsworth)

Improving Conceptual Understanding Through Visual Learning

"Process of interpreting and constructing visual representations to enhance students' understanding of the underlying physics concepts and phenomena"

Expert practice and Multiple Representations

The ability to work with and translate between representations…

- Key scientific ability for reasoning and problem-solving

  Etkina et al., Phys Rev ST PER 2, 020103 (2006)

- Key difference between novice and expert problem solvers

  Dufresne et al., Phys. Teach. 35, 270 (1997)
  Kohl & Finkelstein, Phys Rev ST PER 4, 010111 (2008)

- Can lead to emergent insights into a problem, develops conceptual understanding, and facilitates transfer of knowledge across contexts

  Ainsworth, Learn. Instr. 16, 183 (2006)

Slide Credit: Antje Kohnle (St Andrews)

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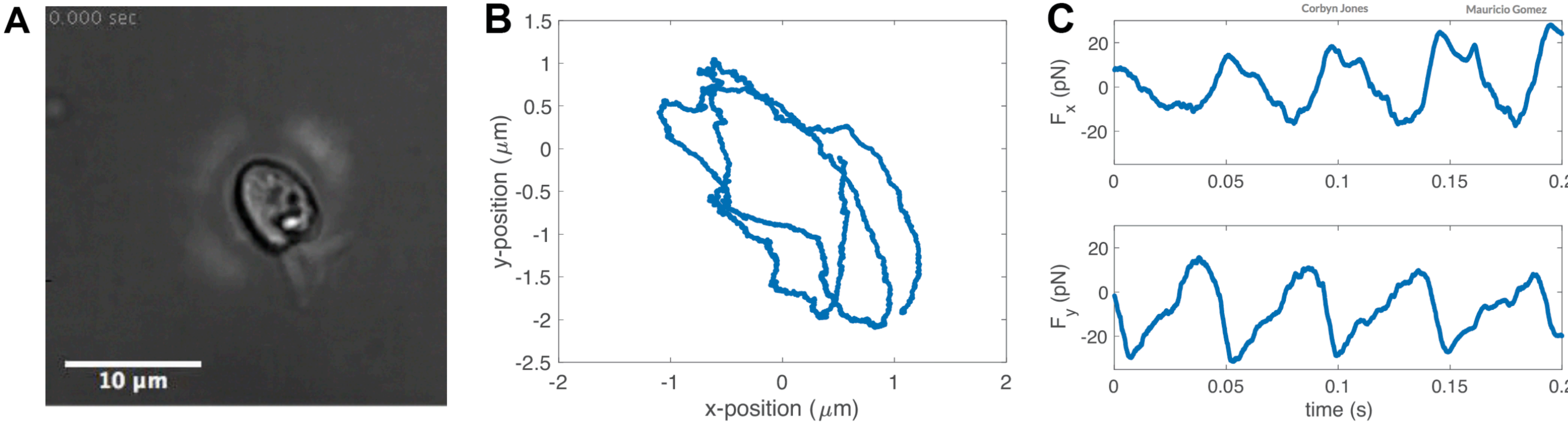
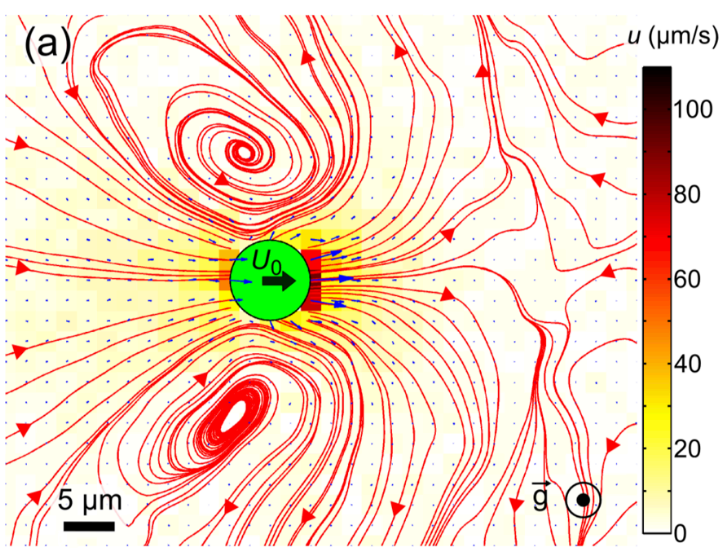
Visual representations are important

Slide Credit: Antje Kohnle (St Andrews)

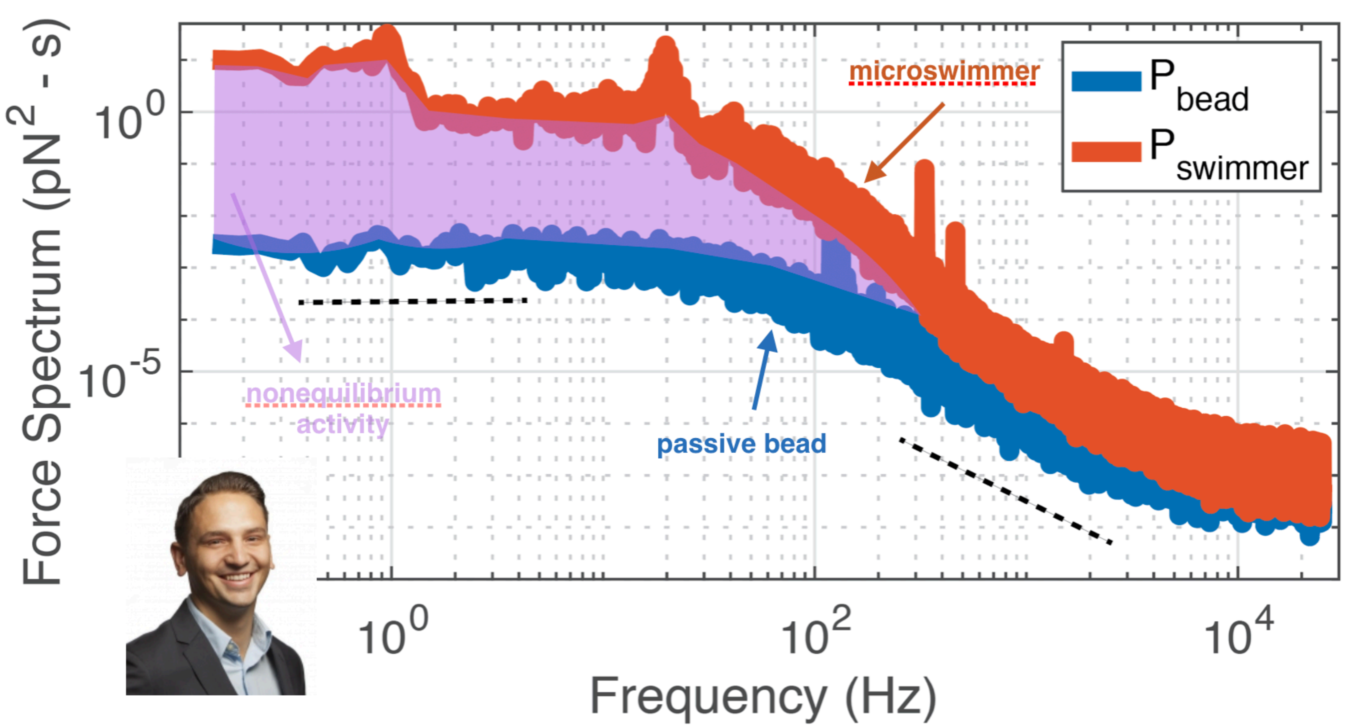
Example research slide

Force spectrum of micro-swimmers



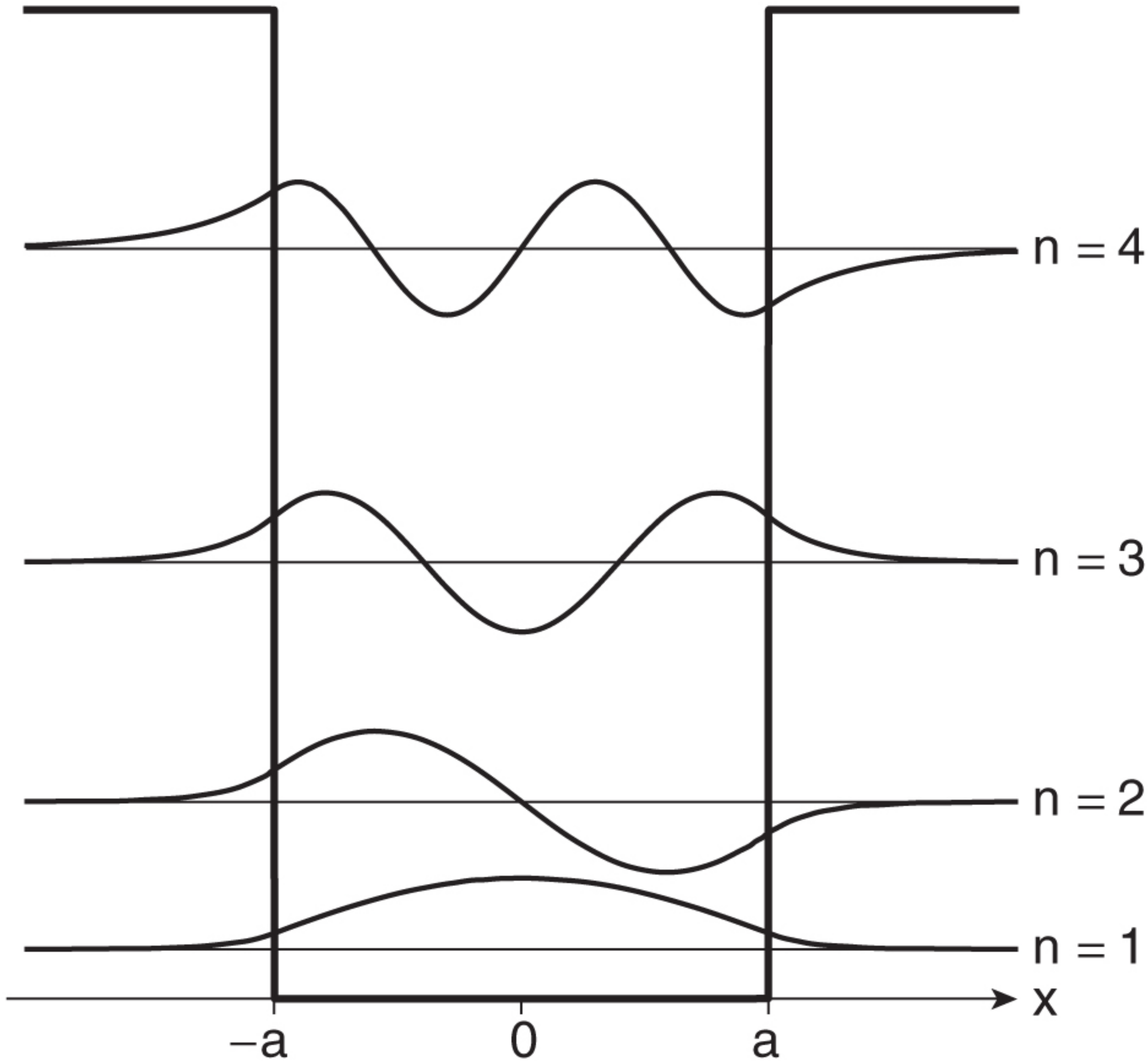


Drescher et al. PRL 2010

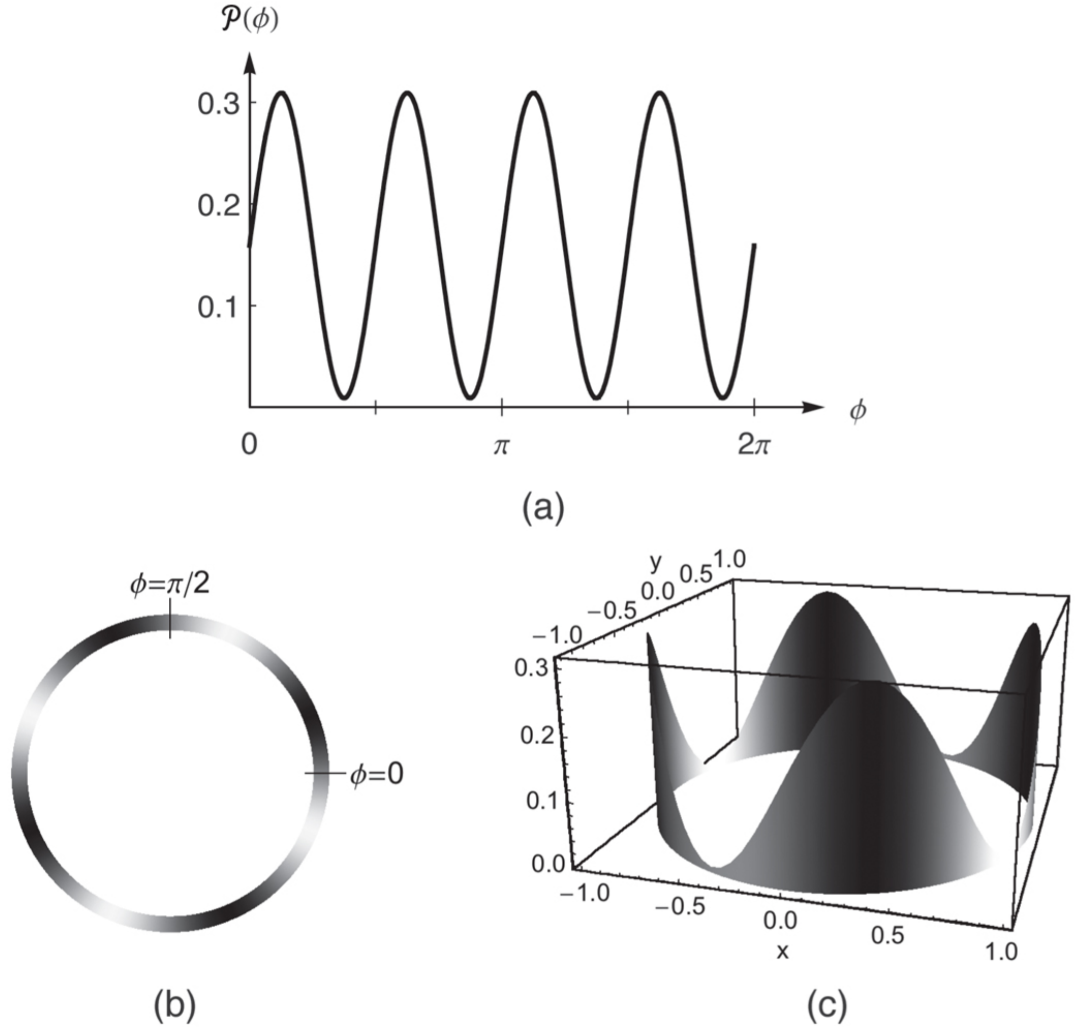


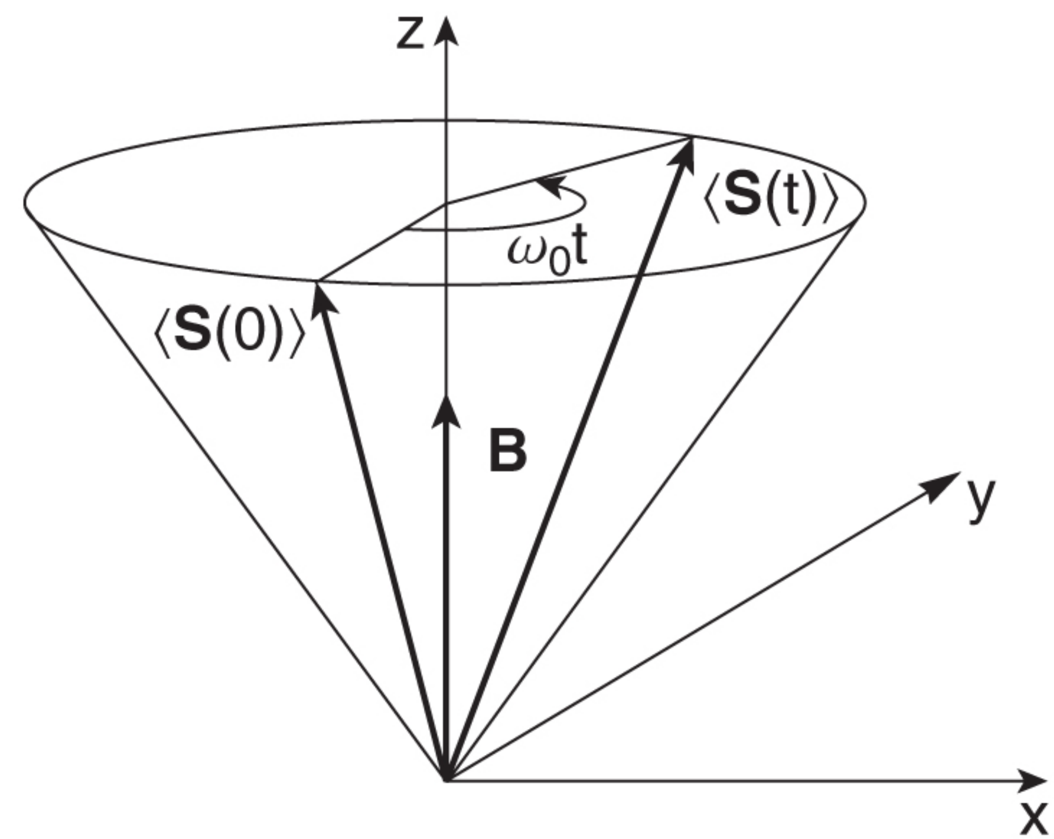
Slide Credit: Wylie Ahmed (CSUF)

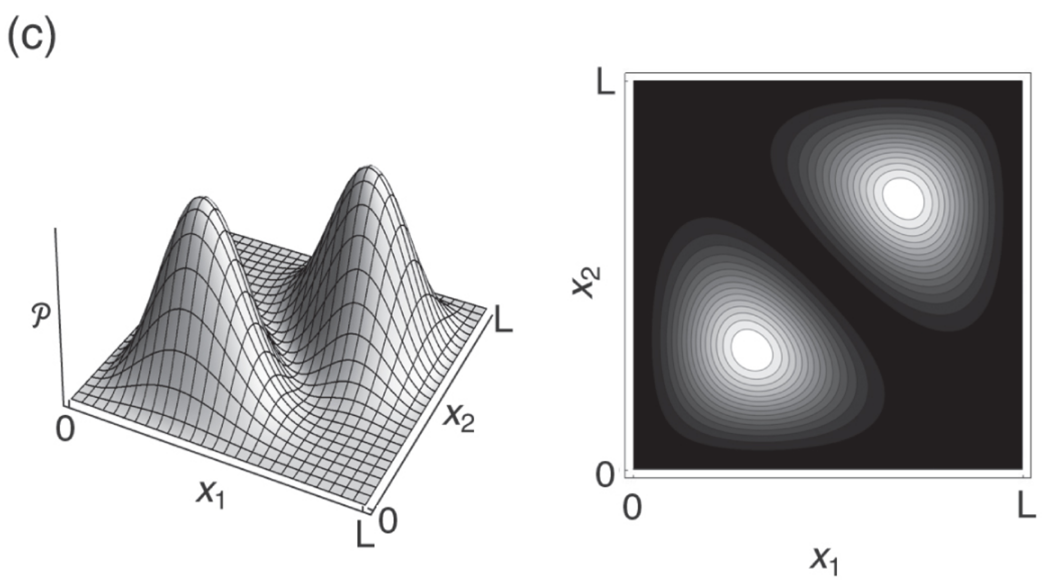
Examples from QM Textbook

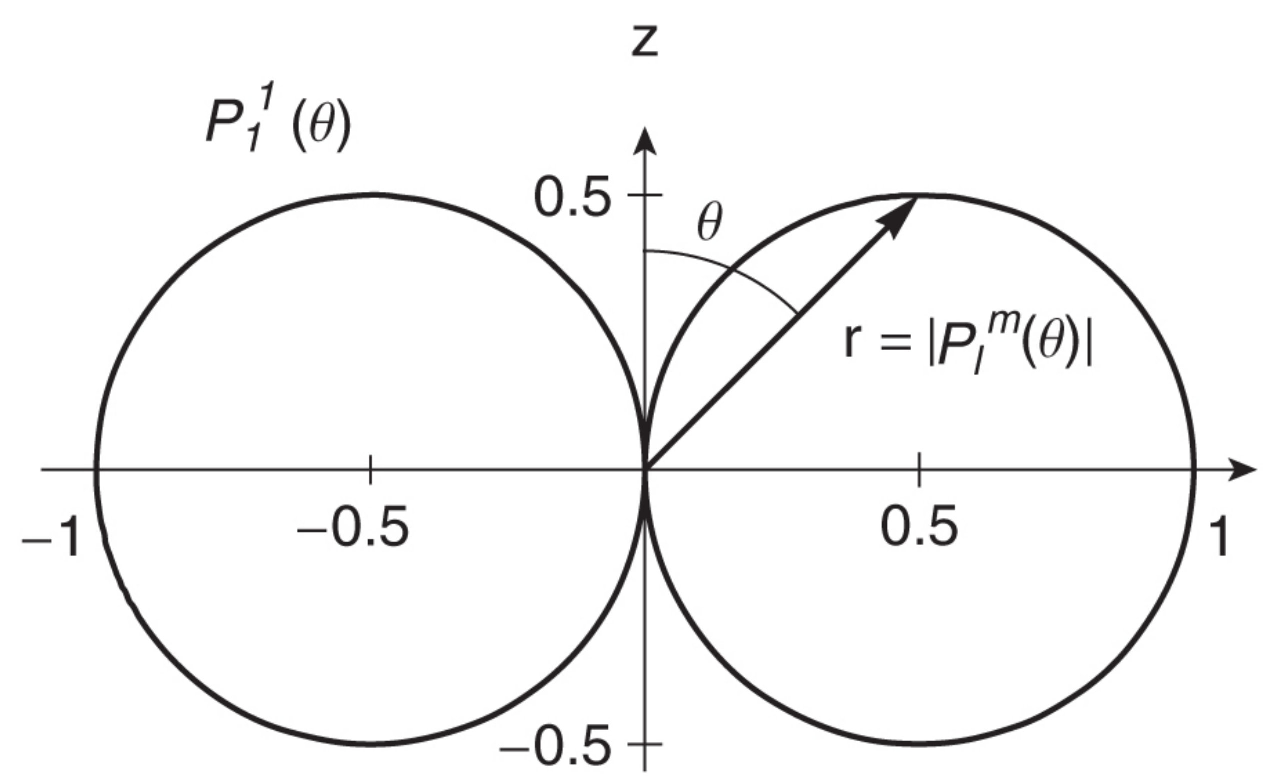


D. McIntyre, “Quantum Mechanics”, Pearson (2013)







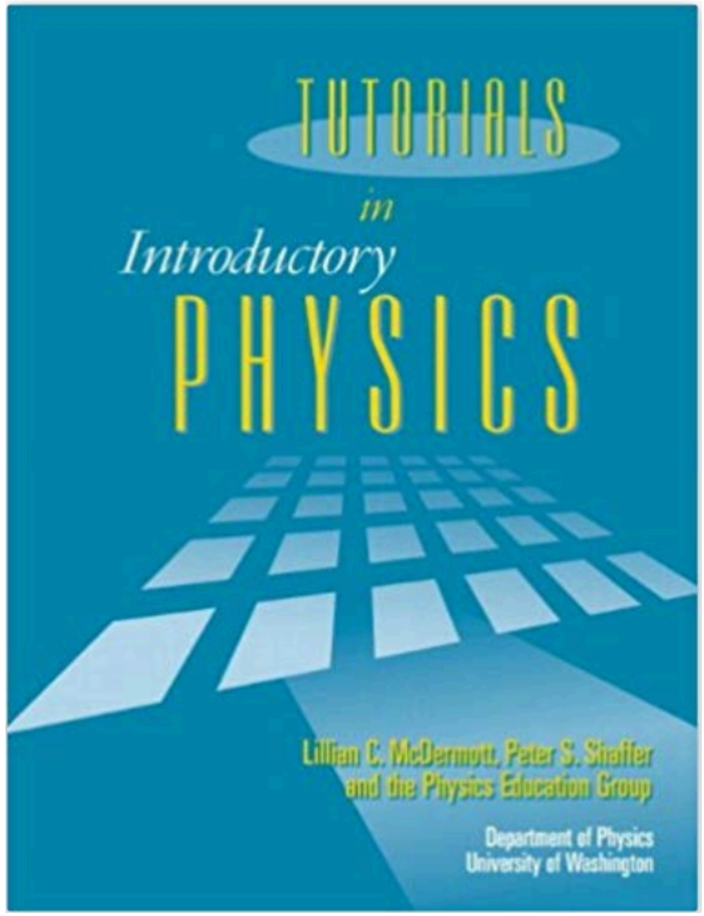


D. McIntyre, “Quantum Mechanics”, Pearson (2013)

Our goal: Develop materials that help develop student proficiency with multiple representations by combining the affordances of interactive simulations and tutorials*

QuVis The Quantum Mechanics Visualisation Project

University of St Andrews www.st-andrews.ac.uk/physics/quvis/



A specific example: Time evolution of quantum states

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Time evolution comes from the Schrödinger equation

$$|\Psi(t)\rangle = \sum_i c_i \, e^{-iE_i t/\hbar} |\psi_i\rangle$$

For example

$$|\psi(t=0)\rangle = \frac{1}{\sqrt{2}}(|\psi_1\rangle + |\psi_2\rangle)$$

$$|\psi(t)\rangle = \frac{1}{\sqrt{2}}(e^{-iE_1 t/\hbar}|\psi_1\rangle + e^{-iE_2 t/\hbar}|\psi_2\rangle)$$

A specific example: Time evolution of quantum states

Time evolution comes from the Schrödinger equation

$$|\Psi(t)\rangle = \sum_i c_i \, e^{-iE_i t/\hbar} \, |\psi_i\rangle$$

Common difficulties:

- One phase
- Ignore imaginary
- Belief that stationary states don't evolve in time

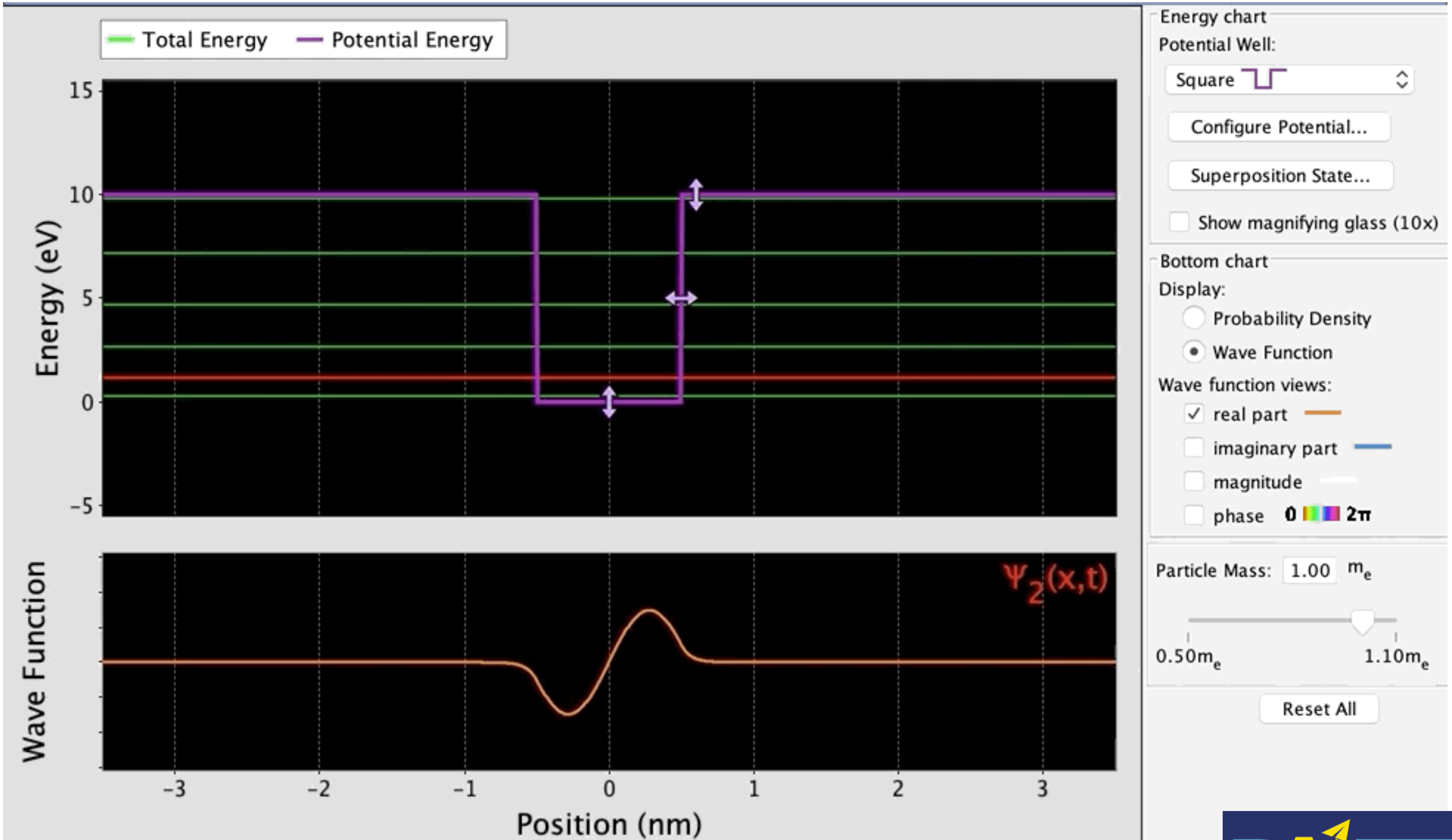
C. Singh, Am. J. Phys. 69, 885 (2001)
H. R. Sadaghiani and S. J. Pollock, Phys. Rev. ST Phys. Educ. Res. 11, 010110 (2015)
P. J. Emigh, G. Passante, and P. S. Shaffer, Phys. Rev. ST Phys. Educ. Res. 11, 020112 (2015)
G. Zhu and C. Singh, Am. J. Phys. 80, 252 (2012)

Example of a common visualization of the time evolution of the ground state:

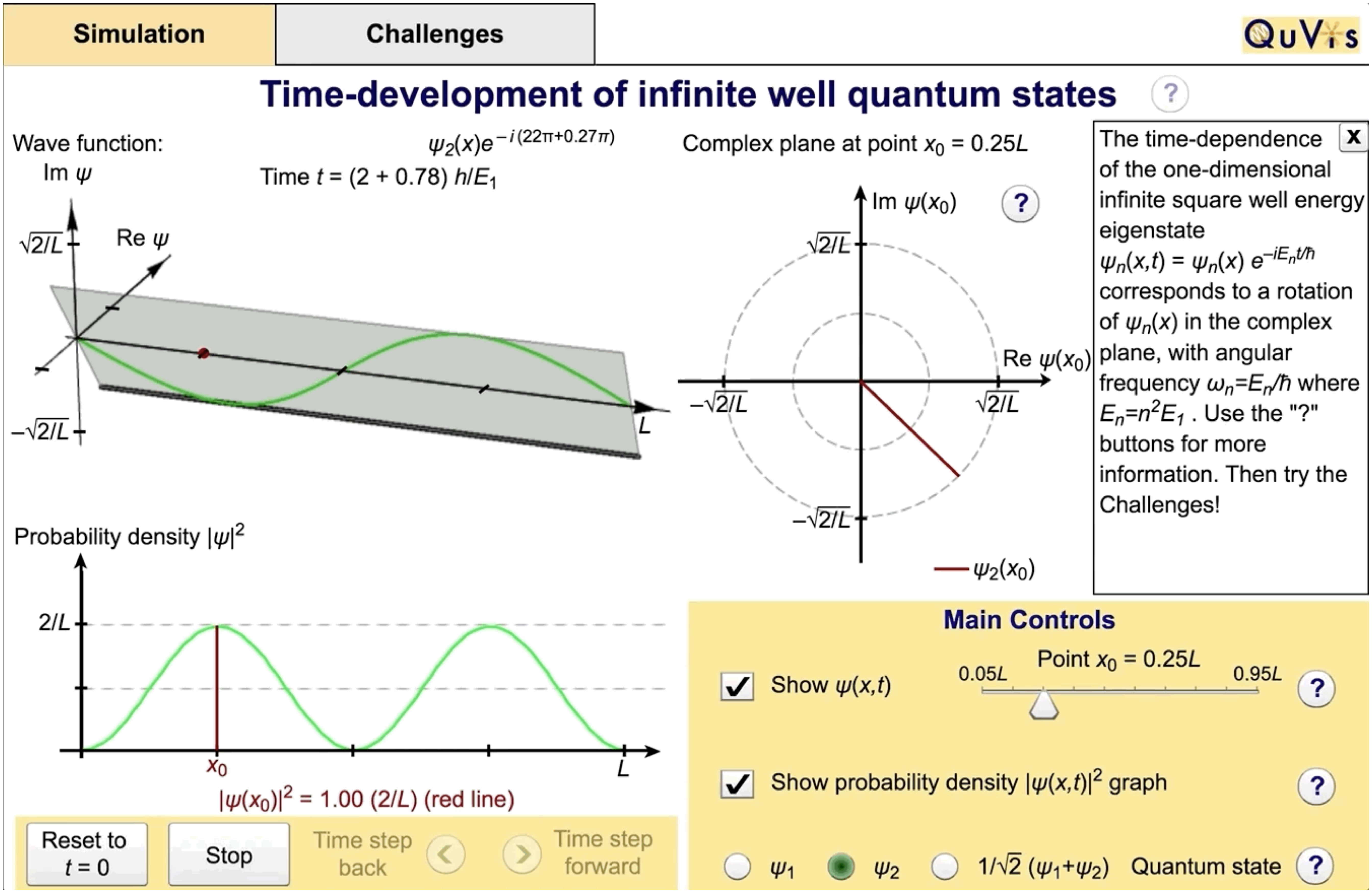
Describe the time evolution of the first excited state of the infinite square well:

Standing wave constantant amplitude

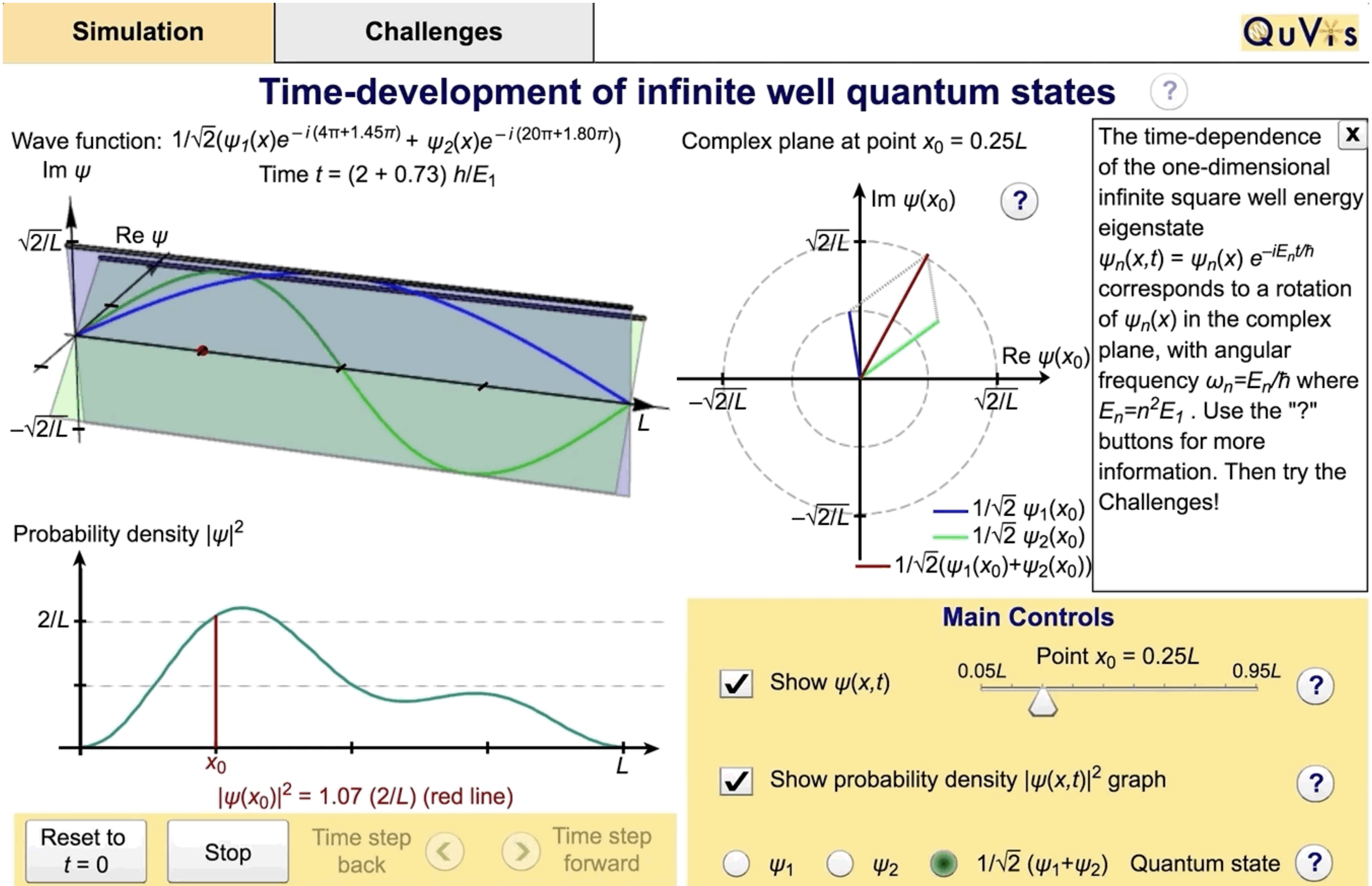
Example of a common visualization of the time evolution of the ground state:



https://phet.colorado.edu/en/simulation/legacy/bound-states



https://www.st-andrews.ac.uk/physics/quvis/simulations_html5/sims/TimeDevelopment/TimeDevelopment.html



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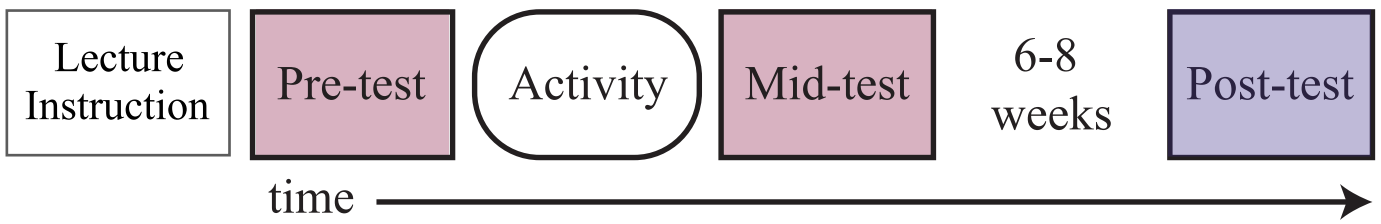
Research Questions:

1. Does visual reasoning improve student performance?

2. Does the simulation-tutorial develop a visual understanding?

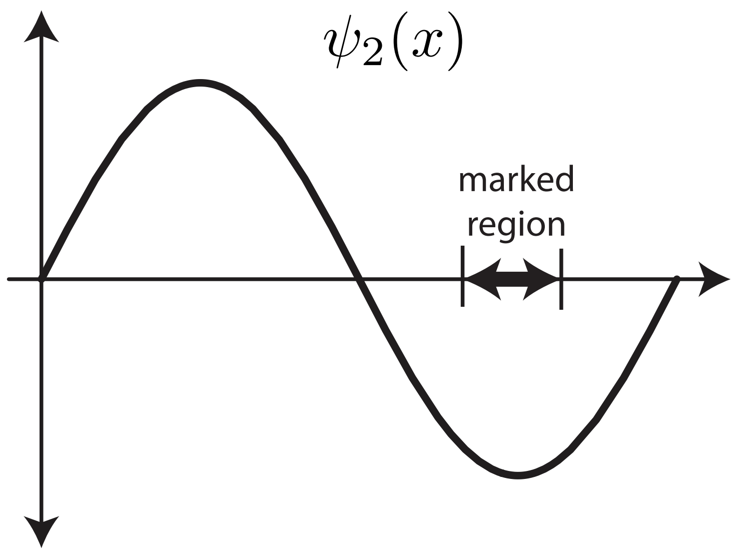
Research Methods:



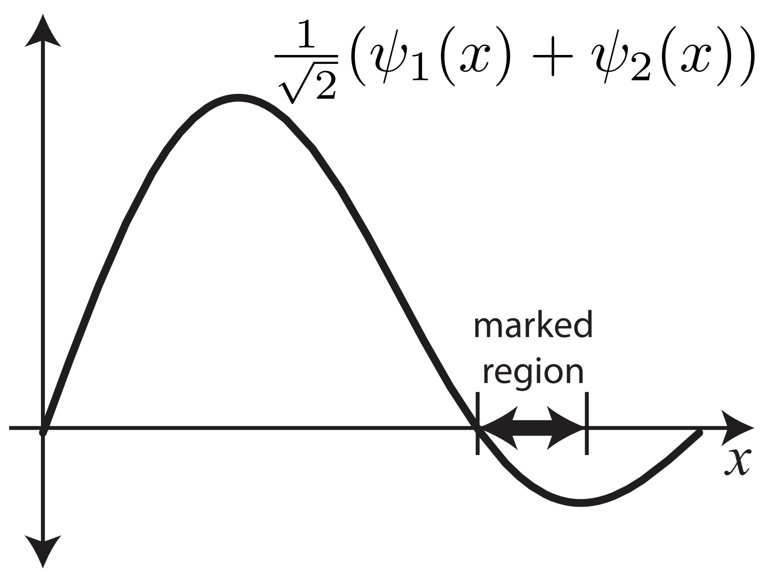
G. Passante & A. Kohnle, PhysRev PER, 15, 10110 (2019)

Pre- and Mid-test:

Describe graphically or in words (not just with formulas) how the full wave function evolves with time.



First excited state



Superposition state

Data analysis

Math:

Real

e^{-t} or similar

Complex

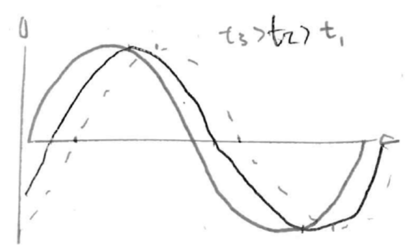
$$\Psi(x,t) = \frac{1}{\sqrt{2}}\left(\psi_1(x)e^{-\frac{iE_1 t}{\hbar}} + \psi_2(x)e^{-\frac{iE_2 t}{\hbar}}\right)$$

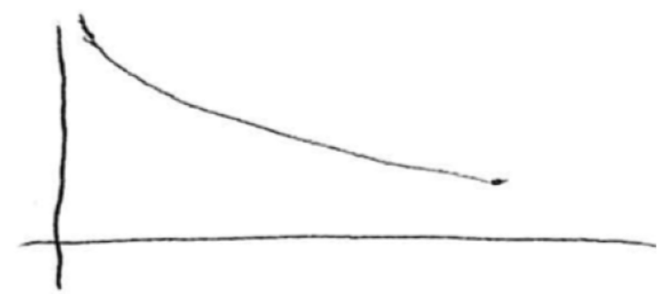
$$\Rightarrow \Psi(x,t) \to 0 \quad \text{as} \quad t \to \infty \quad \text{as before}$$

Visual:

"Classical"

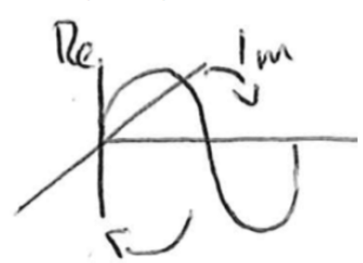
"Wavefunction moves left or right as t increases."





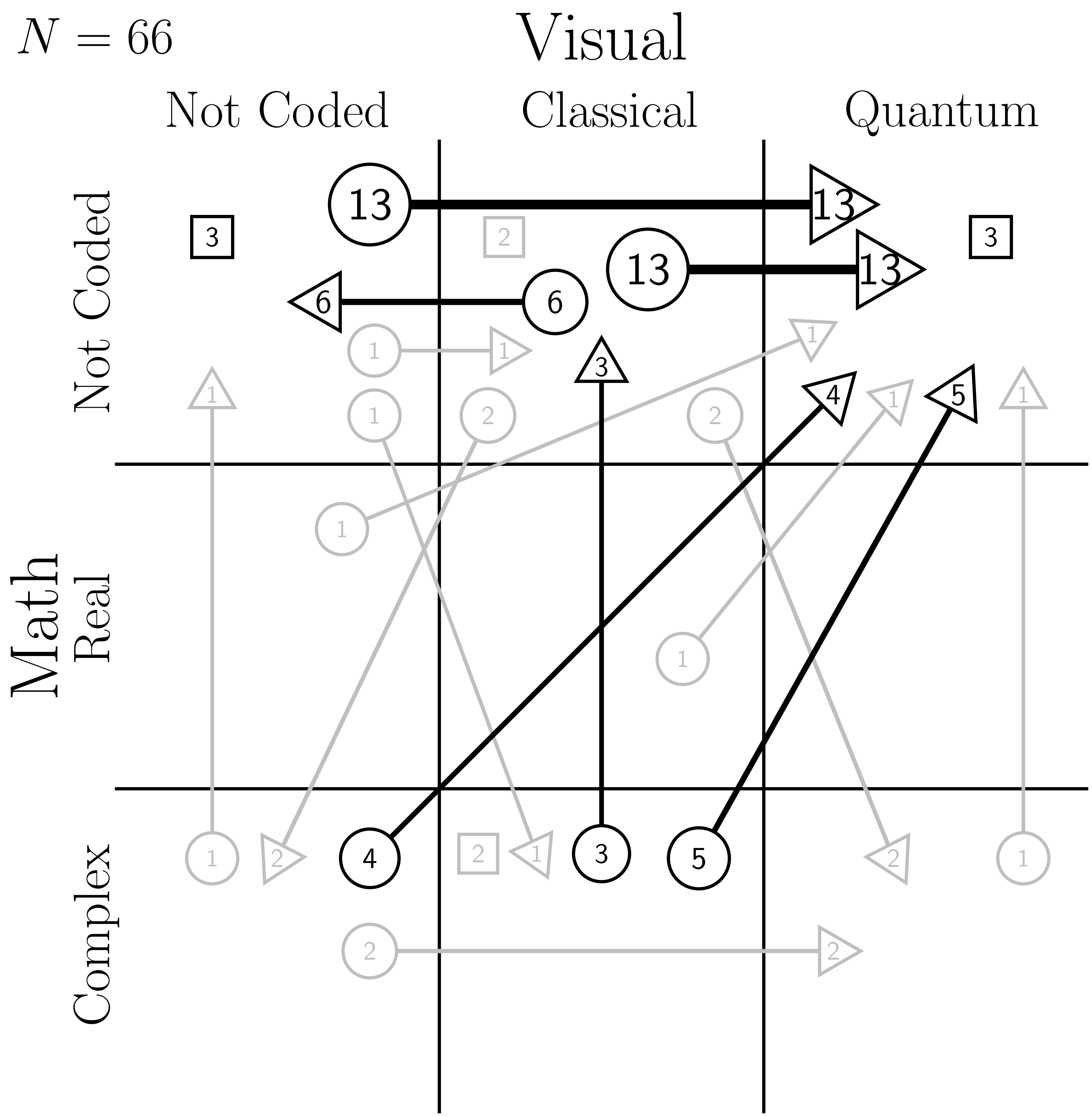
"Quantum"

"$\psi_2(x,t)$ rotates clockwise in the complex plane"

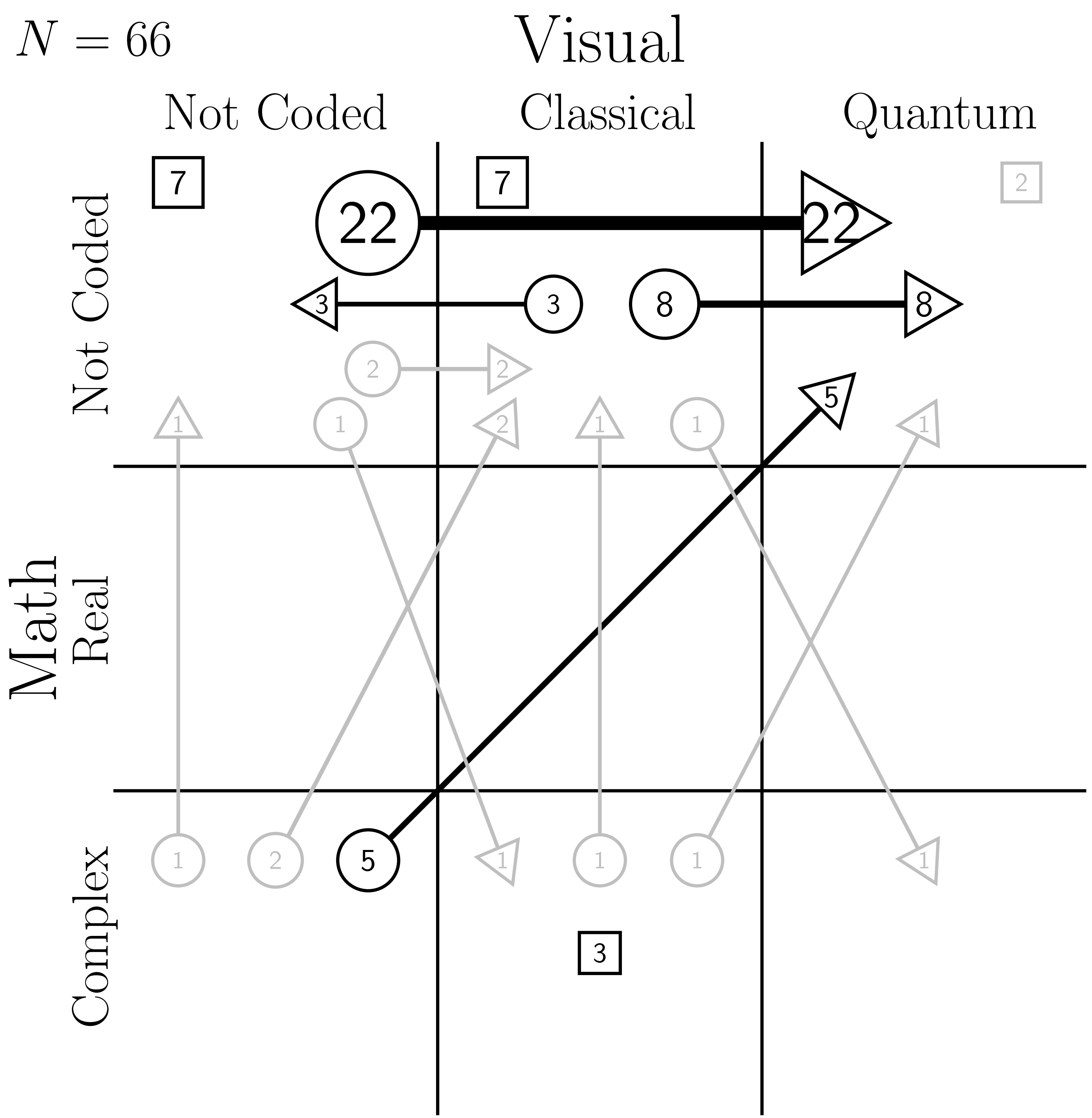


(Responses were also coded for correctness)

Results: Pre ⟶ Mid (First excited state)



Results: Pre ⟶ Mid (Superposition state)



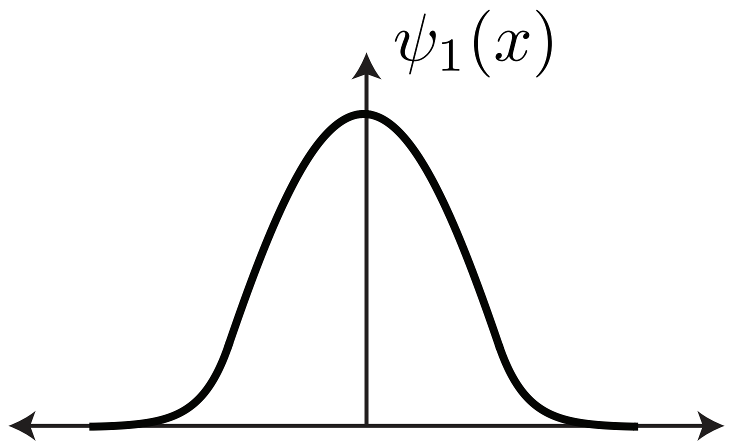
Research Questions:

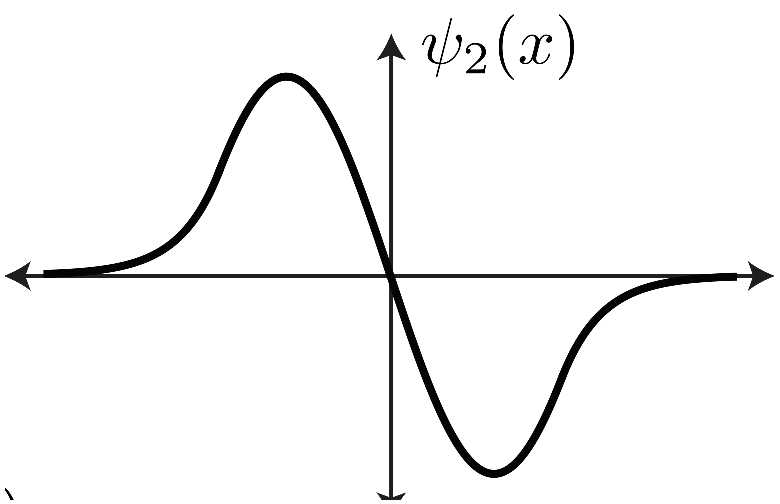
1. Does visual reasoning improve student performance?

2. Does the simulation-tutorial develop a visual understanding?

After the activity, students are more likely to use a quantum visual explanation for how the wave function evolves with time.

Posttest:





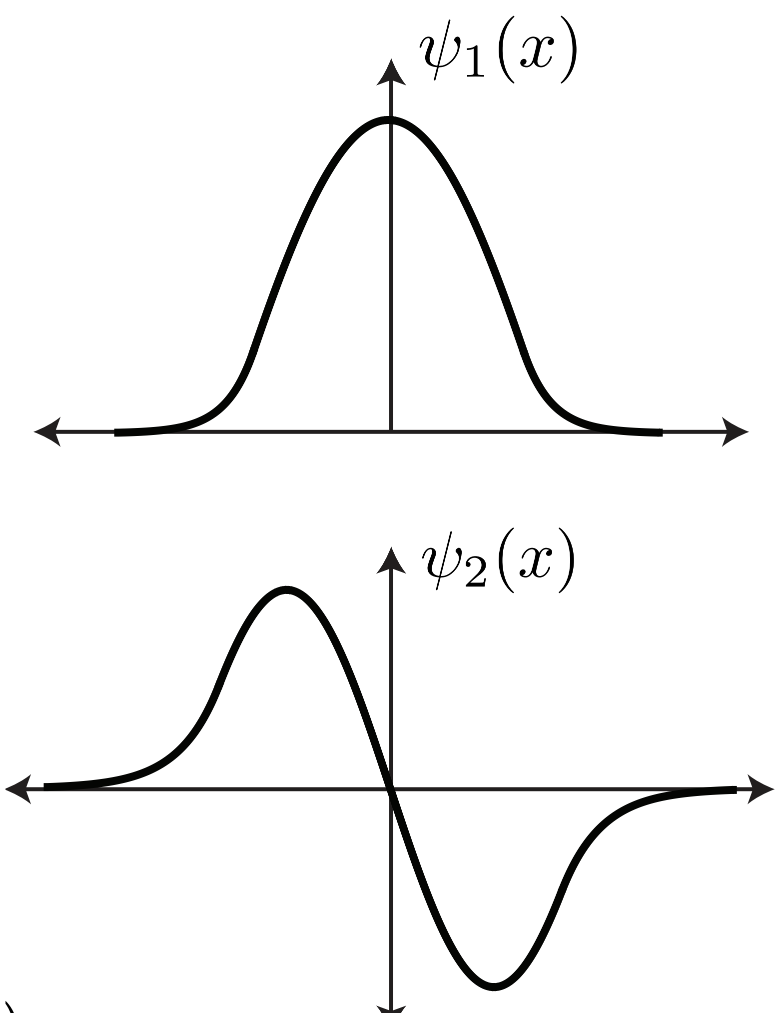
State is initially given by:

$$\psi(x, t = 0) = \frac{1}{\sqrt{2}}(\psi_1(x) + i\psi_2(x))$$

(a) Sketch the probability density for this state at time $t = 0$. Show your reasoning.

(b) Does the probability density for this state depend on time? Explain your reasoning.

Results: Posttest



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(b) Does the probability density for this state depend on time? Explain your reasoning.

	Math	Visual
# responses	43 (50%)	30 (35%)
A Correct	72%	100%
A + Reasoning	54%	73%

Total N = 86

Research Questions:

1. Does visual reasoning improve student performance?

Yes! On an exam question, all students that used a visual explanation got the answer correct (and 73% provided correct reasoning).

2. Does the simulation-tutorial develop a visual understanding?

After the activity, students are more likely to use a quantum visual explanation for how the wave function evolves with time.

The activity works.

Why?

Sketching as a Learning Tool

- Highly successful strategy for learning text

Ainsworth et al., Science 333, 1096 (2011)

- Correlation between sketch accuracy/completeness and posttest performance

Van Meter & Garner, Educ. Psycol. Rev., 17, 295 (2005)

- Sketching supports extraction of conceptually relevant information

Mason et al., Contemp. Educ. Psychol. 38, 211 (2013)
BUT Ploetzner & Fillisch, Learn. Instr. 47 (2017)

Shaaron Ainsworth
University of Nottingham
(Learning Sciences)

Slide Credit: Antje Kohnle (St Andrews)

Simulation-tutorials have a two-part structure:

Phase 1: Without simulation support

Prepare students to work with the simulation

Phase 2: With simulation support

Develop and advance their understanding of time evolution and the affect on various quantities.

Kohnle, Ainsworth, and Passante (in preparation)

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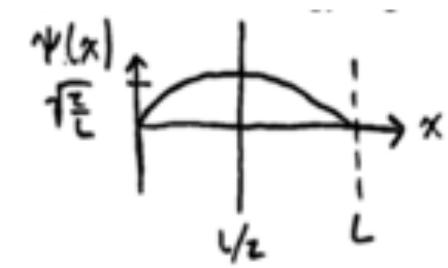
Abbreviated Question Text	Example Sketches	Role of Sketching
A Sketch the ground state energy eigenfunction at $t = 0$.		Sketch to activate prior knowledge

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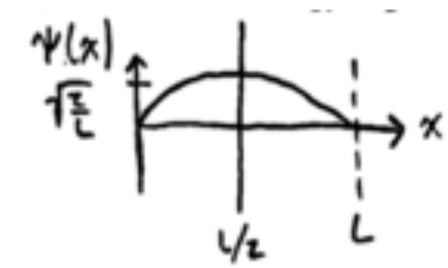
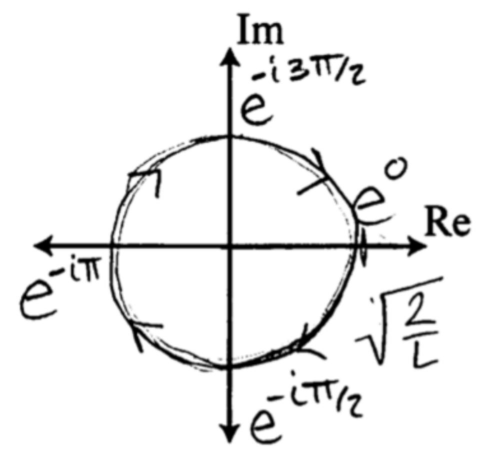
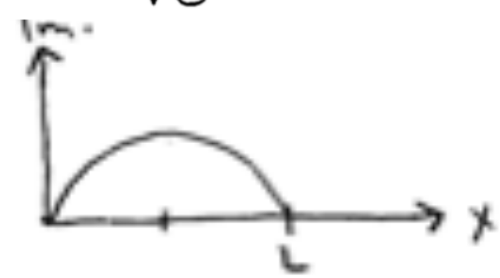
A	Sketch the ground state energy eigenfunction at $t = 0$.		Sketch to activate prior knowledge
B	Plot the time evolution of $\psi_1(x)$ at $x = L/2$. Describe this evolution in words.		Sketch to transform
C	Sketch $\psi_1(x, t)$ at time $E_1 t/\hbar = 3\pi/2$		

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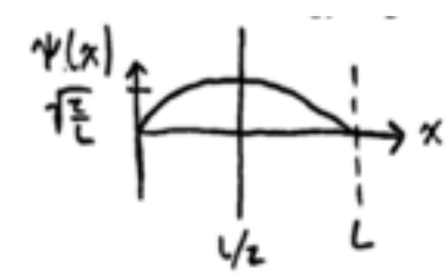
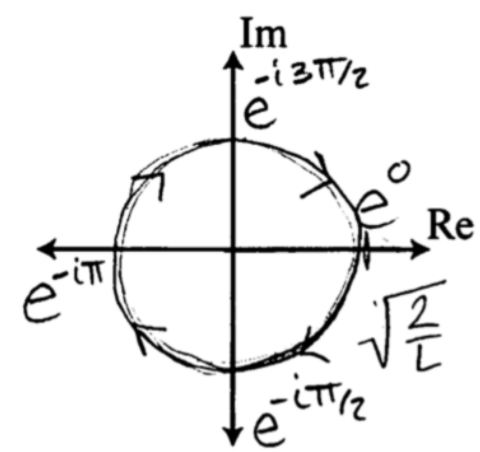
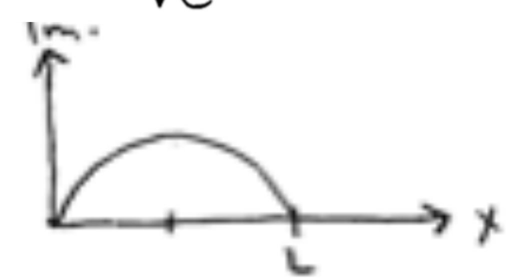
A	Sketch the ground state energy eigenfunction at $t = 0$.		Sketch to activate prior knowledge
B	Plot the time evolution of $\psi_1(x)$ at $x = L/2$. Describe this evolution in words.		Sketch to transform
C	Sketch $\psi_1(x, t)$ at time $E_1 t/\hbar = 3\pi/2$		
D	How would you plot the time evolution for the entire function using a 3D representation?		Sketch to invent

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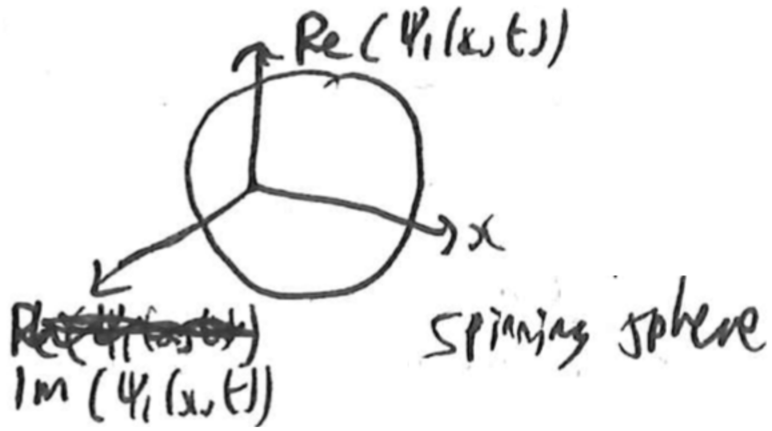

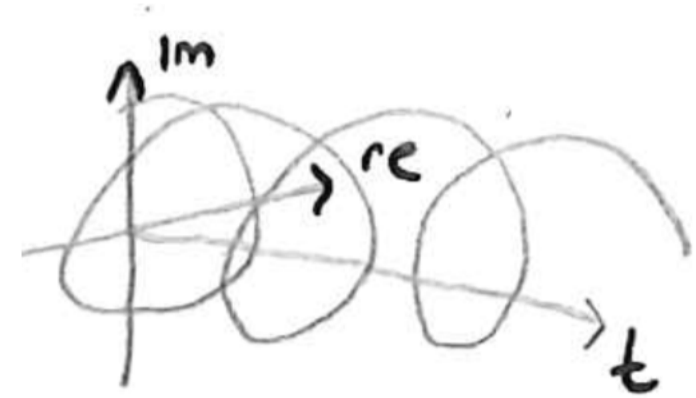

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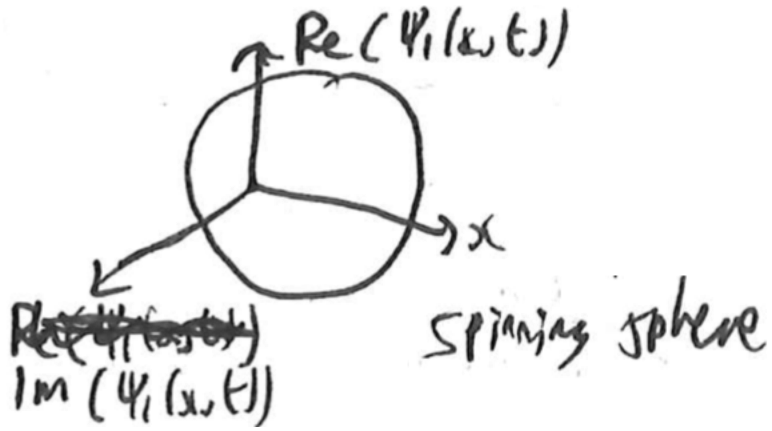

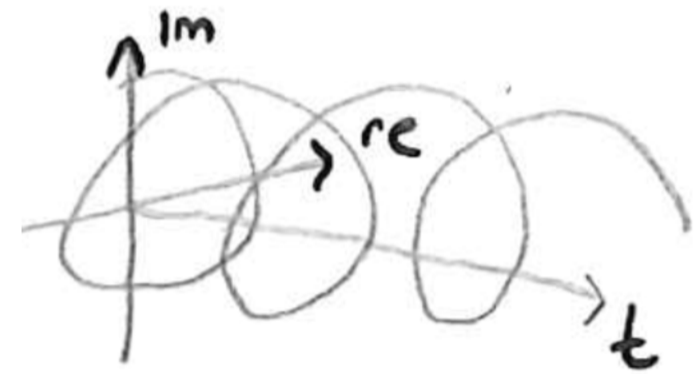

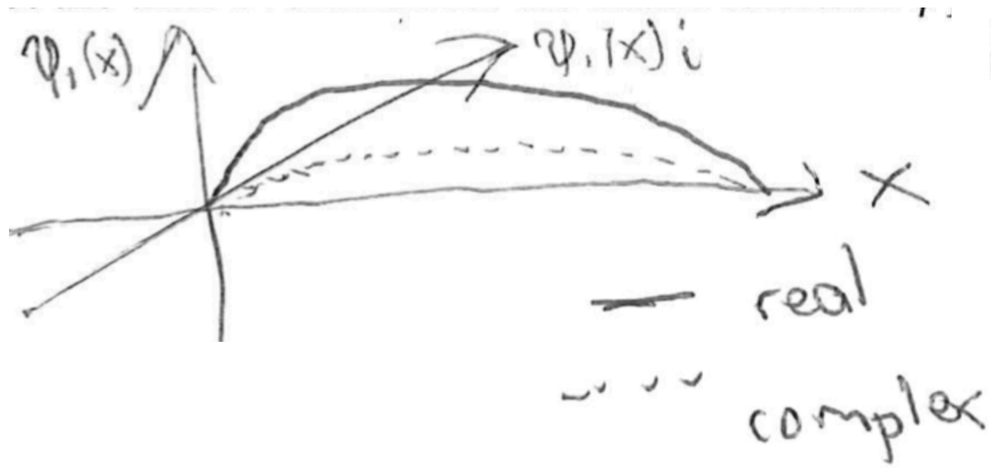

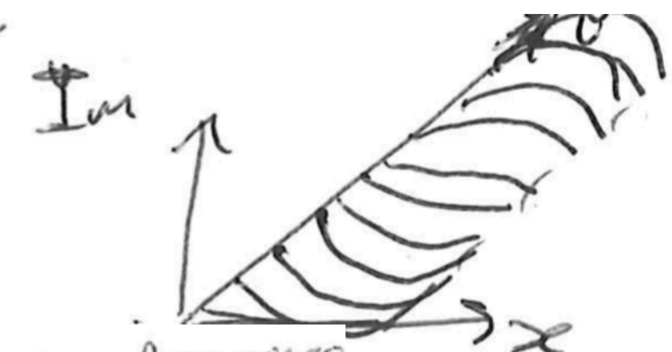

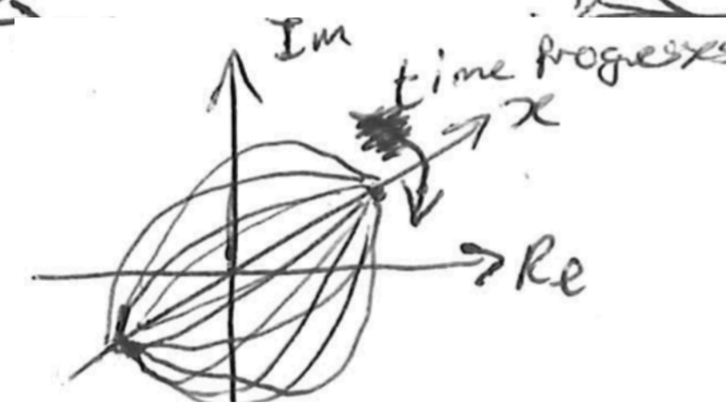

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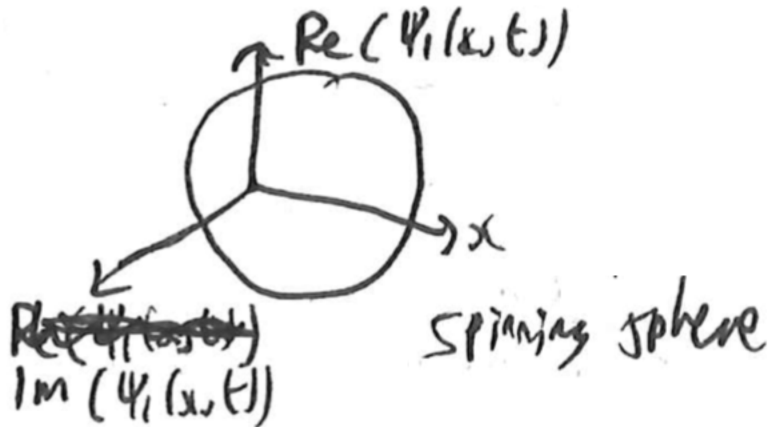

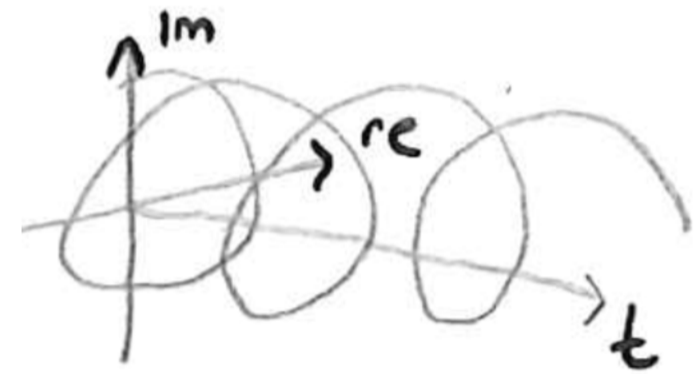

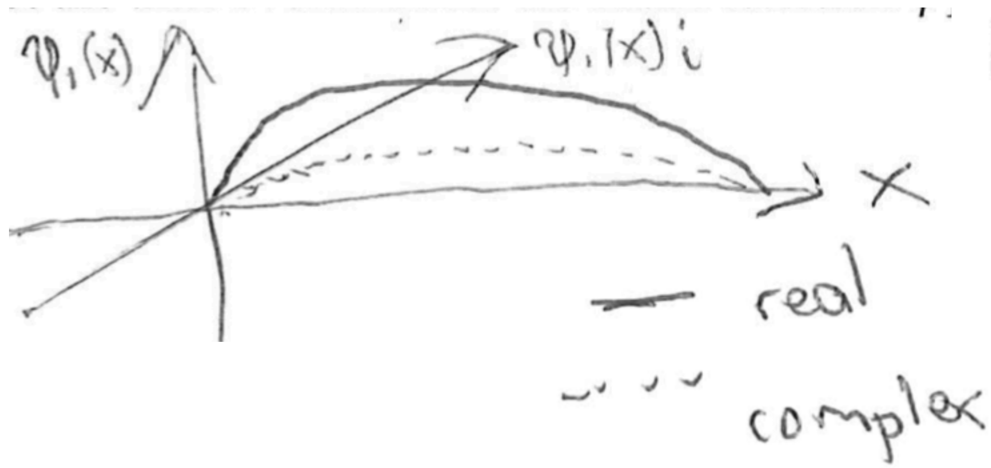

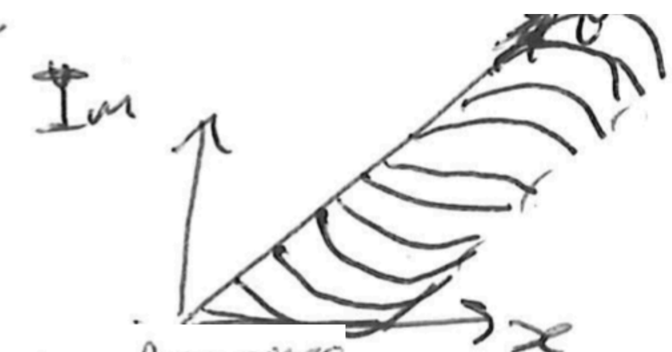

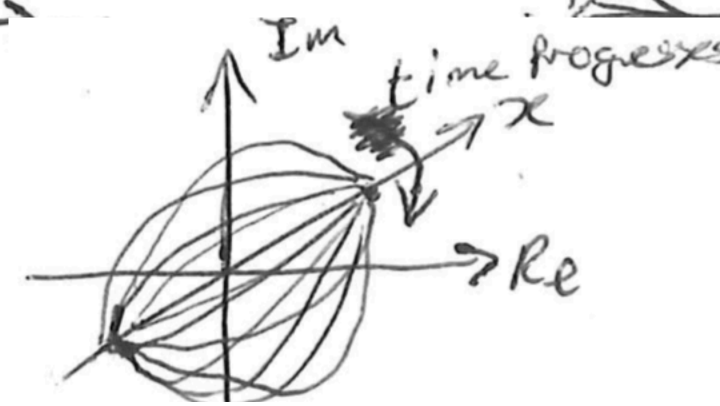

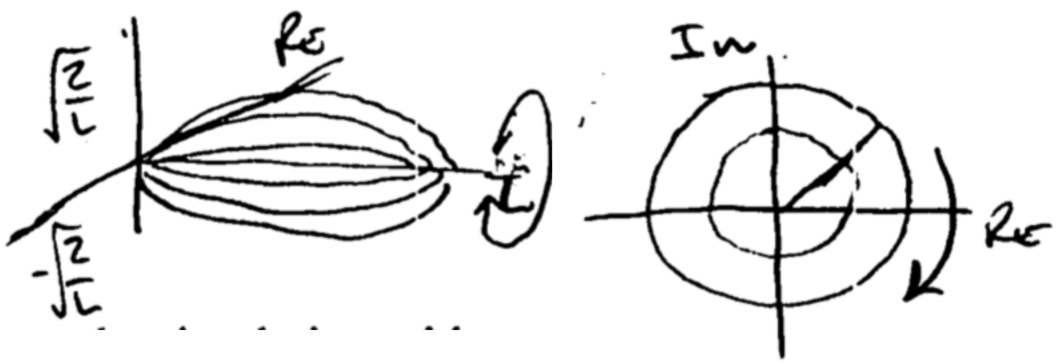

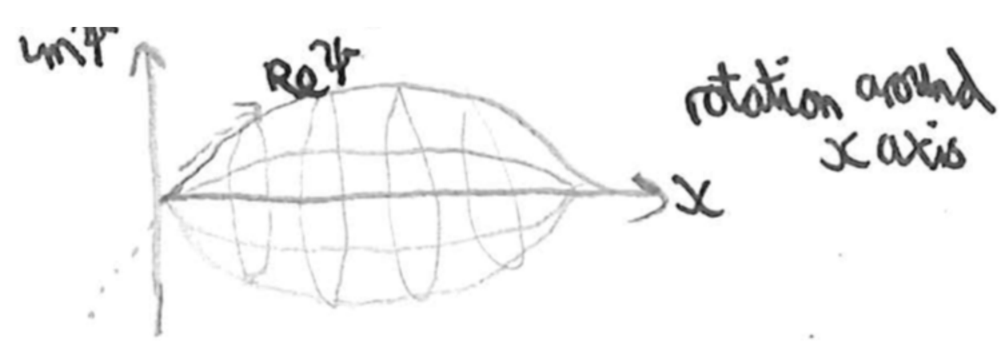

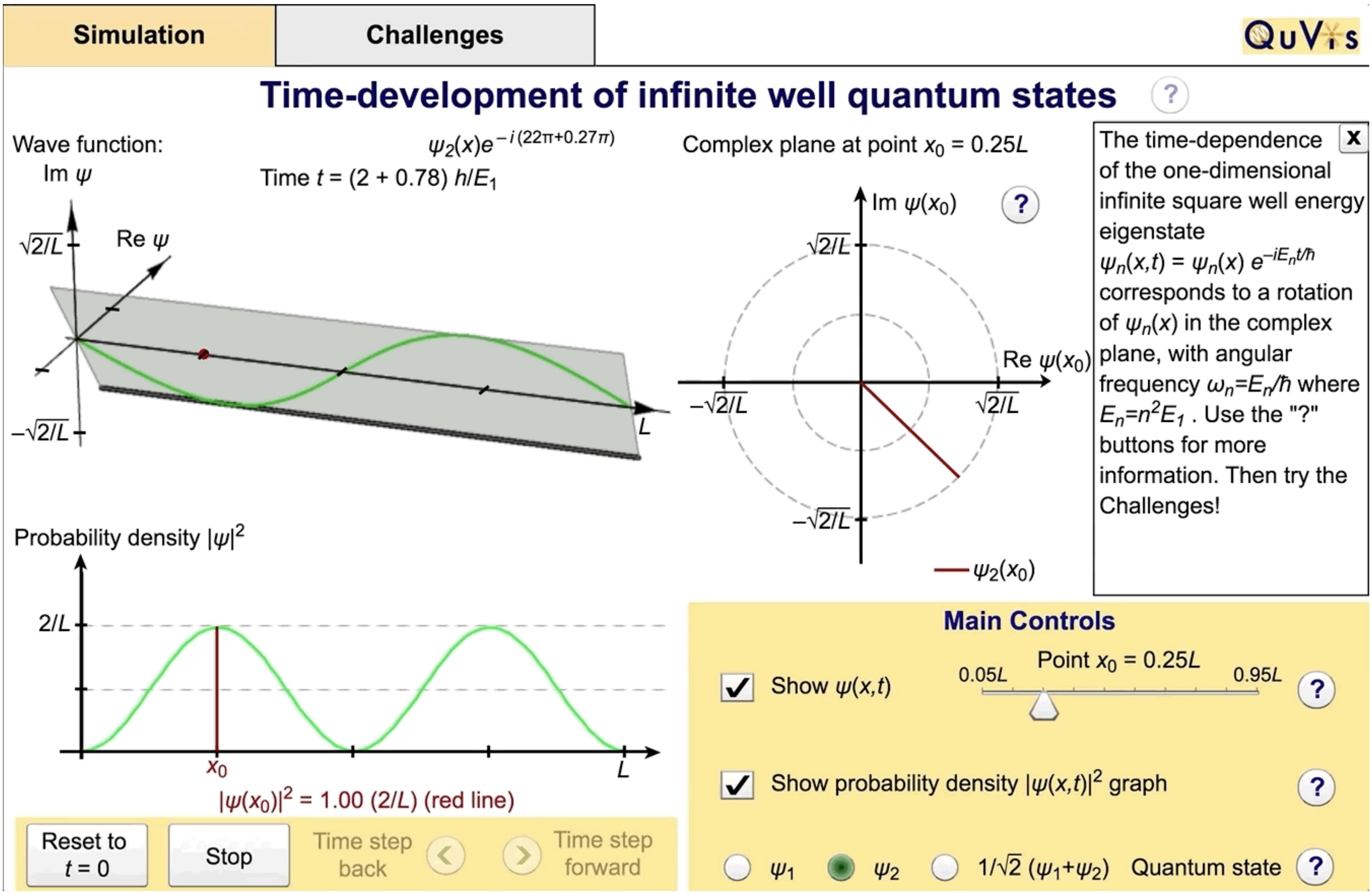

https://www.st-andrews.ac.uk/physics/quvis/simulations_html5/sims/TimeDevelopment/TimeDevelopment.html

Thank you

Gina Passante - gpassante@fullerton.edu

Some useful links:
Curricula: physport.org/curricula/ACEQM
QuVis Sims: www.st-andrews.ac.uk/physics/quvis/

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FULLERTON

NSF

PER @ CSUF
Group

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Antje Kohnle
Shaaron Ainsworth
Steven Pollock
Homeyra Sadaghiani
Natasha Holmes