Thinking like a Physicist: The Paradigms Curriculum at Oregon State University

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Presented at the 2008 March Meeting of the American Physical Society, New Orleans, LA

www.physics.oregonstate.edu/paradigms
Outline

- Thinking like a physicist
- Paradigms/Capstones in Physics
  reorganize content, new pedagogy
- Computation
- Solid state & nanoscience examples
  from the courses
- Research projects
Thinking like a physicist

Physics knowledge

Critical, analytical thinker
ability to generalize

Consummate problem-solver

Capacity for self-, peer-, lay-instruction

Multiple representations

Creativity intuition independence

Computational skill

Conceptual skill

Mathematical skill

Experimental skill
Multiple Representations

• Algebraic

\[ b_n = \frac{2}{\lambda} \int_{0}^{\lambda} f(x) \sin \frac{n2\pi x}{\lambda} \, dx \]

• Geometric

• Graphical

• Verbal

A periodic function can be represented as a sum of harmonic sinusoidal functions whose coefficient is the projection of that function onto the relevant harmonic.

The extent to which harmonic is represented in the sum has profound consequences for the quantum wave function, the electrical signal, etc.
# Paradigms & Capstones

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Characteristics of Paradigms

- Case-study method (small pieces)
- Explicit attention to middle-level transition
- Active engagement
- Span 2 or more subdisciplines
- Early Quantum Mechanics
- Quantum & Classical base
- Collaborative faculty planning (buy-in)
Active Engagement

• Verbalization teaches clear thinking
• De-emphasize teacher-as-oracle
• Activate intuition
• Active problem solving
• Encourage peer-instruction
• Efficiency
Computation in the Paradigms

• OSU offers B.S. in Computational Physics; first course in Maple and Java feeds Paradigms
• Visualization
• Calculation
• Simulation
• Animation
• Requires literacy, but not expert coding skills
• “Reach for the computer” to solve a problem
Computation in the Paradigms

- Spins & Quantum Measurement via Stern-Gerlach simulation
- Projection; superposition; change of basis
- Same language as Fourier analysis
- “Real” experiment to determine quantum state

Oven → z-Analyser → x-Analyser → z-Analyser → result?
Solid State & Nanoscience

- Spend time on fundamental ideas and ways of thinking; later complexity is more easily understood.
- Early quantum mechanics
- Couple to modern ideas
  - Quantum wells
  - Carbon nanotubes
  - Semiconductors & defects
  - Spin valves, GMR
- Motivation to learn more
- Opportunity to do research
- Attention to professional development
- AJP journal paper; 10-minute talk
Quantum Wells to Bands

GaInP/AlInP Quantum Well Laser Diode

Relevant, modern examples
Quantum Wells to Bands

Boundary conditions, eigenstates, and Schrödinger’s equation all have to do with producing light
Periodic Square Wells

- Periodic square well develops energy band concept and defect idea
- Qualitative and quantitative
Doped Semiconductor (Si:P)

- Learning a different dialect is useful!
- Explicit instruction

**Chemist’s picture**

- [Ne] 3s² 3p²
- [Ne] 3s² 3p³

**Engineer’s picture**

- $E_g$

**Real picture**
Dispersion: waves in a rope

- Easy, familiar, but rich example
- Dispersion concept is new
- Normal modes, superposition, boundary conditions, experiment, limits

- Measure normal mode $\lambda$, $f$
- Measure $\tau$, $\mu$
- Plot $\omega$ vs. $k$
Coupled Oscillators

- Students find period and wavelength from simulation
- CUPS DOS-based software (revision in progress)
Diatom chain

Dispersion, gaps, modes, boundaries, evanescent waves
Real Bandstructure - Si

\[ \vec{k} = \left[ \frac{k}{\sqrt{3}}, \frac{k}{\sqrt{3}}, \frac{k}{\sqrt{3}} \right] \]

\[ \vec{k} = [k, 0, 0] \]
Superposition

• LCAO approach to solids: need molecular orbitals, density of states, and partial density of states
• Begins with Fourier analysis in *Oscillations*
• Continues with Stern-Gerlach in *Spins*
• Finite well in *Waves* & H-atom in *Central Forces*
• Superpositions in *Quantum Mechanics*
Bandstructure; DoS computation

- Senior solid state class
- Analytical: cubic systems, single-orbit models in LCAO approach
- Computation: Modern research tool
- Real-world materials are too complex for class, but relevant to student research
- Web-based interface
- Focus on physics, not computation
- Future: simpler interface

http://www.wien2k.at/
Bandstructure; DoS computation

- Students produce plots of density of states, partial density of states of real materials
- Dispersion $E(k)$ plots, understand direct and indirect gaps, effective masses etc.
Carbon Nanotubes

- Dispersion relation for graphene
- Metallic & semiconducting NTs
Senior Research Projects

- Start in junior year
- Work with faculty & grads
  - attend group meetings
  - hands-on in lab
  - present at local conferences
- Writing course in Winter of senior year
  - peer feedback & faculty guidance
- Write thesis
- 10-minute talk in spring of senior year at departmental Senior Thesis Conference
Take-home message

- Explicit attention to development of professional skills
  - Multiple representations
  - Active engagement
  - Careful attention to basics reaps rewards later
  - Peer-instruction and problem solving
  - Computation

- Curriculum:
  - Shorter, concept-based paradigms
  - Longer, sub-discipline-based capstones
  - Research expectation

- Solid State & Nanoscience
  - Modern examples all through curriculum
  - Solid knowledge basis
  - Information is everywhere; analytical and critical thinking must be taught!
Acknowledgements

- National Science Foundation
  DUE-0618877,-0231194,-9653250
- Oregon State University
  Department of Physics, College of Science, Academic Affairs, lots of faculty time!
- Solid State/Nano Curriculum:
  Janet Tate, William Warren
  Guenter Schneider, David McIntyre,
  Henri Jansen
- Current grant PIs:
  Corinne A. Manogue (Director)
  David McIntyre
  Tevian Dray, Barbara Edwards (Math)
  Emily van Zee (SMEd)
Extra slides
CNT-based coaxial cable

• Co-ax cable lab teaches wave reflection at medium discontinuity

Rybczynski et al, APL 90, 021104 (2007)
Quantum-classical connection

Tunneling through barrier

Evanescent wave in loaded string

Relevance: Magnetic tunnel junctions, STM, tunnel diodes, skin depth ....
Multiple Representations

Can your juniors connect these? Or, given one, generate the others? There are many, many concepts here we think are simple, but which most students have at best a very fuzzy idea. If you’re afraid of the basic problem, how can you make progress?

\[ V(\vec{r}) = \frac{1}{4\pi\varepsilon_0} \int \frac{\rho(\vec{r}')}{|\vec{r} - \vec{r}'|} dV' \]

The potential at a field point \( P \) a distance \( r \) from the origin is the sum of the potentials at that point due to each element (located at \( r' \)) of the extended charge distribution.
Spherical Harmonics in Color

- Multiple representations

\[ |Y_{10}(\theta, \phi)|^2 \]