Enhancing physics students' conceptual understanding and problem-solving skills

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The Higher Education Academy Physical Sciences Centre

Centre for Higher Education Research

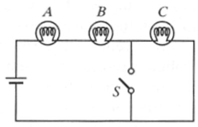
IOP Institute of Physics

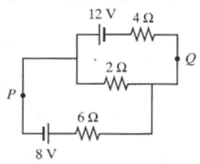
University of St Andrews 600 YEARS

Outline

- Conceptual understanding
  - The QuVis quantum mechanics simulations
- Problem-solving ability
  - Explicit teaching of problem-solving strategies in level two physics
  - Problem-based learning projects in level one physics

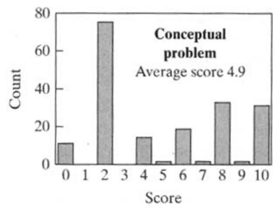
When the switch S is closed, which of the following increase, decrease, or stay the same? intensities of bulbs A and B, intensity of bulb C, current drawn from the battery, voltage drop across bulb A, total power dissipated

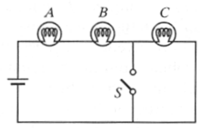


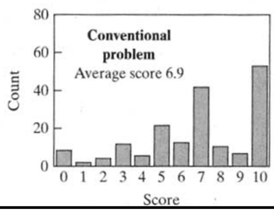


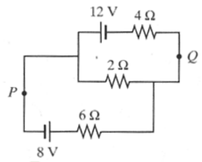
Calculate the current in the 2 Ω resistor and the potential difference between points P and Q.

[E Mazur, Peer Instruction, 1997]







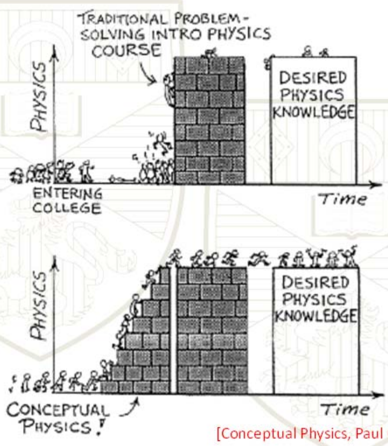


[E Mazur, Peer Instruction, 1997]

Conceptual understanding

- It is possible for students to do well on conventional problems by memorizing algorithms without understanding of the underlying physics.
- Conceptual knowledge can improve a student's ability to perform calculations. It is decisive for those problems requiring a transfer of knowledge to new contexts.

[Carr and McKagan, Am J Phy, 2009, E Mazur, Peer Instruction, 1997, Thacker et al, Am J Phys 1994]



[Conceptual Physics, Paul G. Hewitt, Instructor's Manual]

Motivation: challenges in learning quantum mechanics

- May be perceived as abstract and far-removed from reality.
- Counterintuitive outcomes of observations and theory.
- Students may become proficient at calculations, but still have difficulties interpreting their results conceptually.
- Large number of studies investigating student difficulties in quantum mechanics and interpretative understanding. e.g. Bao et al 2002; Domert et al 2005; McKagan et al 2008; Singh 2008, Baily and Finkelstein, 2009
- Research-based resource development (activities, animations and simulations, conceptual questions and surveys) e.g. Wuttiprim et al., 2009; Belloni et al 2006; Zhu and Singh, 2012

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Potential of simulations

- Enhance engagement and exploration through interactivity and prompt feedback.
- Multiple representations, including visual representations of abstract concepts and microscopic processes that cannot be directly observed.
- Visualization of mathematically challenging processes (wave packets, time dependence) which are useful for gaining insight and physical intuition.
- Research-based development tailors resources to student needs.

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PhET simulations (University of Colorado)

phet.colorado.edu

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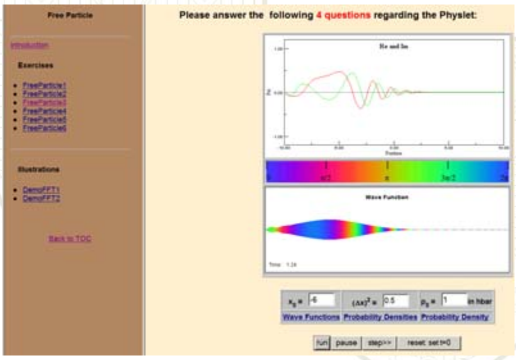
Quantum Physics Physlets



http://webphysics.davidson.edu/physlet_resources

Belloni, Christian, and Cox, *Physlet Quantum Physics*, 2006.

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OpenSource Physics packages

www.opensourcephysics.org

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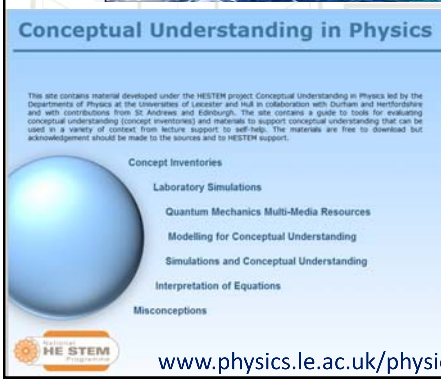
HESTEM project Conceptual Understanding in Physics



Project lead: Derek Raine (Leicester)

www.physics.le.ac.uk/physicsconcepts

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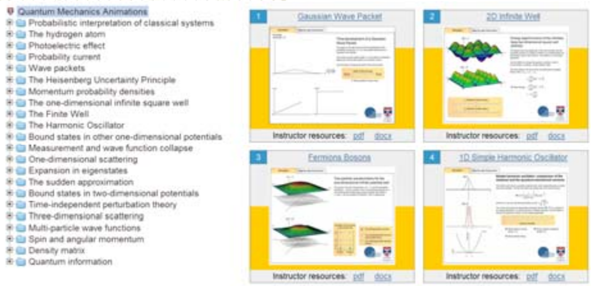
Overview of the QuVis animations

- Since 2009; aimed at University students and instructors
- Based on outcomes of education research and our lecturing experience (four quantum mechanics lecturers involved)
- Each animation aimed at clarifying a particular concept; includes a step-by-step exploration that explains key points.
- Evaluation (questionnaires, diagnostic surveys, observation sessions) used to optimize the animations.
- Complementary to other multimedia resources
- Freely available at www.st-andrews.ac.uk/~qmanim for use online or download.
- QuVis team: Antje Kohnle, Donatella Cassettari, Tom Edwards, Alastair Gillies, Georg Hähner, Christopher Hooley, Natalia Korolkova, Bruce Sinclair + many students: Gytis Kulaitis, Cory Benfield, Aleksejs Fomins, Joseph Llama, Callum Ferguson, Liam Atkinson, Emma Robertson

Kohnle et al., Eur J Phys, 31, 1441 (2010)
Kohnle et al., Am J Phys, 80, 148 (2012)

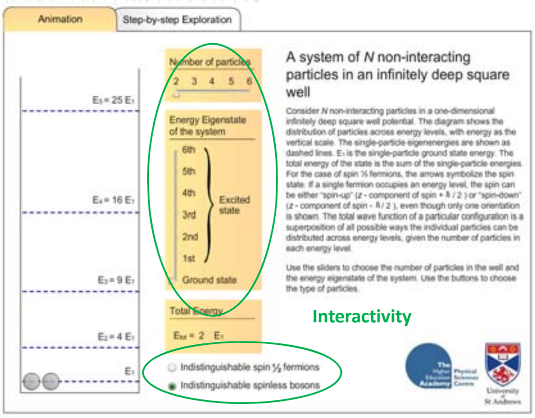
Animation topics



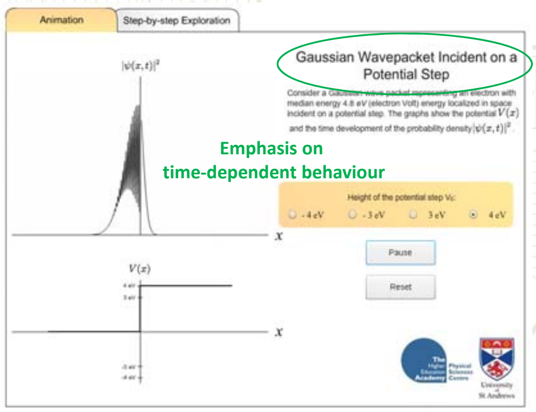
50 animations developed to date; wide range of topics.

Range from introductory to advanced undergraduate level

Key features of the animations



Key features of the animations



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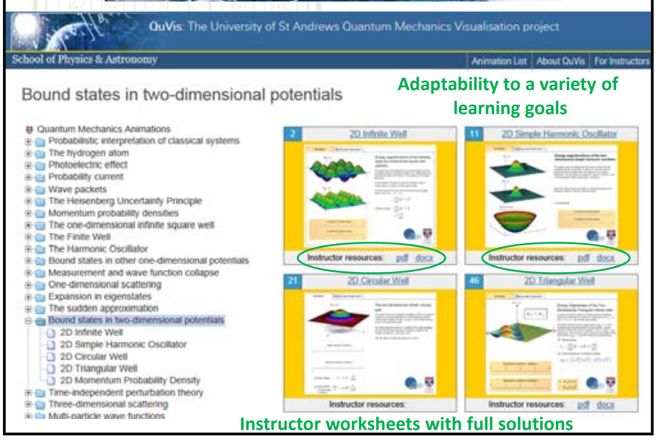
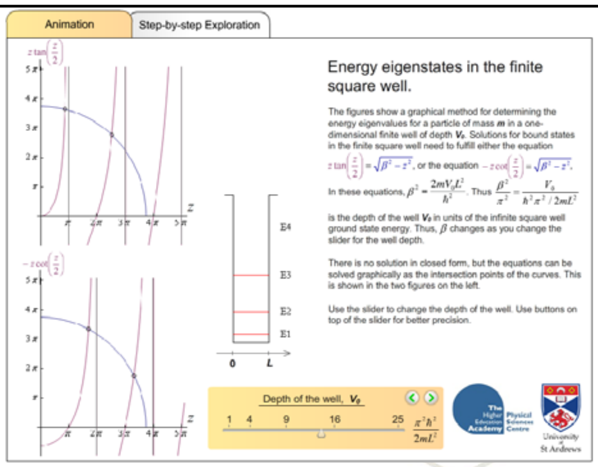
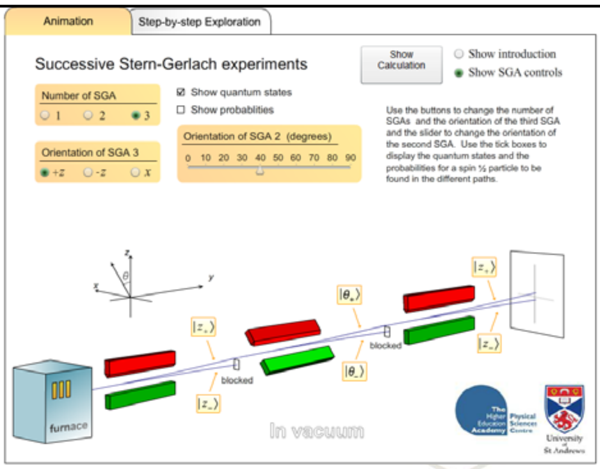






Evaluation methods

Evaluation drives interface design and content. Evaluation outcomes used to optimize all animations.

- Student questionnaires in two qm courses, assessing student attitudes towards and use of the animations.
- An 11-item diagnostic survey to evaluate learning gains.
- Observation sessions with a small number of student volunteers, some of this work carried out at two institutions (the Universities of Edinburgh and St Andrews).
- Facilitation of a workshop session in which students work with two animations.

Student observation sessions

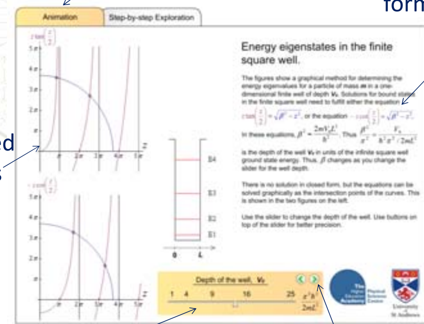
- Individual sessions with student volunteers, carried out in 2010 and 2012.
  - students asked to "think aloud" while interacting freely with a previously unseen animation
  - questions aimed to test whether graphs and explanations make sense
  - follow-up interview on experience with this and previous animations
- Consistency in issues raised. Outcomes used to optimize interface design and content of all animations.

Example: Revisions due to evaluation outcomes

Coloured tabs (2011)

Colour in formulas (2012)

Improved graphics (2011)

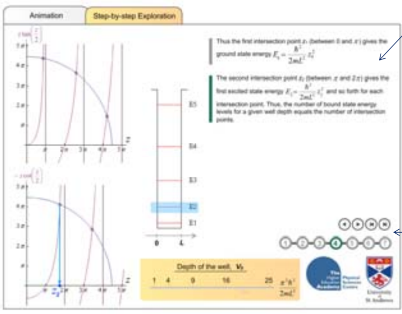


Colour to highlight controls (2011)

Additional button controls (2011)

Example: Revisions due to evaluation outcomes

Additional animated steps explaining relation between intersection points and energy levels (2012)

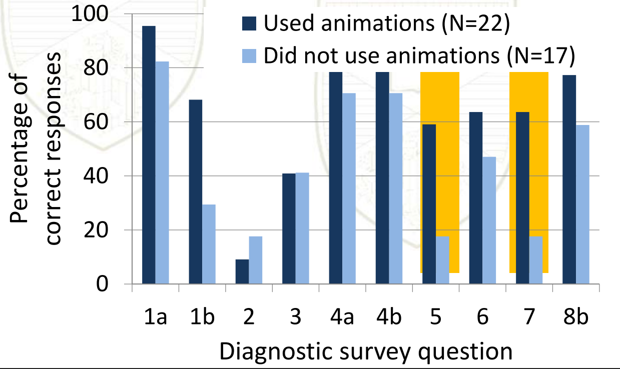


Step counter and clearer step controls (2011)

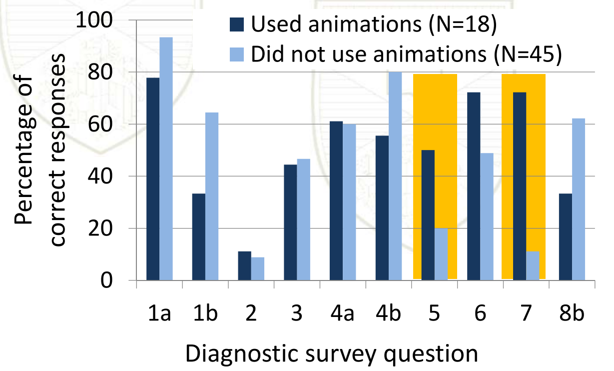
Steps with user interactivity (2012)

Diagnostic survey outcomes 2011

Questions 5 (Potential Step) and 7 (Finite Well) covered topics where level two students had used animations in a workshop.



Diagnostic survey outcomes 2012

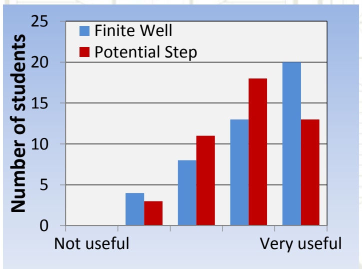


Diagnostic survey outcomes

+ reproducible result, explanations of reasoning of students that had used the animations showed greater understanding and not recall; greater confidence in their answer.

– students had one hour more practice on these topics, survey a few days after the session. No comparison with other resources on the same topics.

Level 2 questionnaire outcomes



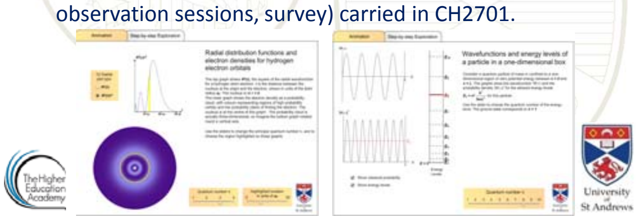
"They were incredibly useful. It's good to get "hands on" with what sometimes feels like a "hands off" topic."

"I was especially confused in visualizing solutions for the finite-depth square well, but animations of the graphs really helped me understand the concepts"

N=61, 2010 results

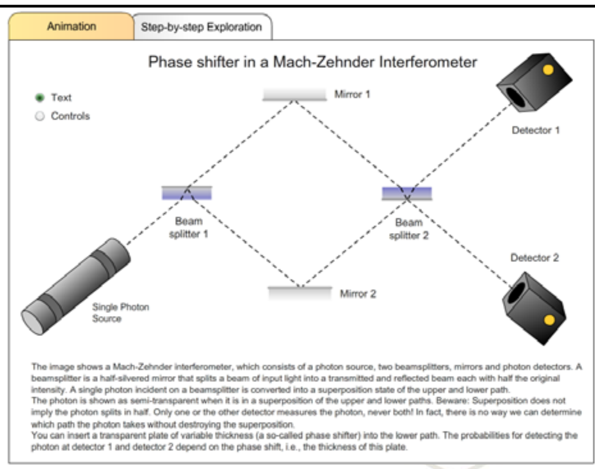
Animations for chemistry students

- Aim: Tailor animations to chemistry students studying introductory quantum mechanics by modifying existing animations, developing new animations and developing resources for chemistry instructors.
- Pilot site www.st-andrews.ac.uk/~qmanim/chemistry proofing still ongoing. Initial evaluation (student observation sessions, survey) carried in CH2701.



The IOP New Quantum Curriculum Project

- Will provide learning and teaching materials for a modern approach to a first course in quantum mechanics starting from simple two-level systems.
- Text written by experts in the fields of quantum information theory and foundations of quantum mechanics.
- Collaboration between the Universities of Sheffield, Loughborough, Leicester, St Andrews, York and University College London. St Andrews is developing animations for this project.
- Materials will be freely available on an IOP website summer 2013. Development and evaluation work will continue in the following years.



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How experts differ from notives

Expert-novice differences in problem-solving ability well studied
[Chi et al. (1981); How people learn (2000)]

- Experts notice meaningful patterns of information
- Content knowledge that is organized around core concepts and conditionalized.
- Flexible retrieval of information, representational fluency
- Metacognition: monitoring one's level of understanding

Problem-solving ability

- Progress in teaching problem-solving skills
  [Heller et al. (1992), Leonard et al. (1996), Ogilvie (2009), Gaigher et al. (2007), Warren (2010)]
  and in assessing them
  [Docktor and Heller 2009].
- Video analysis to enhance problem-solving
  [eg Brown and Cox 2009, Wehrbein, W. M., 2001]

Development of problem-solving ability in second-level physics

- Since 2011/12: Bruce Sinclair and Antje Kohnle + BSc students Mark Gaskell and Christopher Hill
- Aims: improve and assess problem-solving ability in our level two physics. Introduce video problems to create more real-world context.

Explicit teaching of problem-solving strategies in second level physics

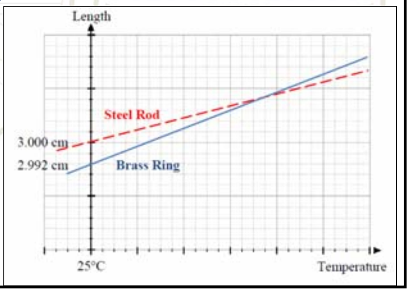
- **2011/12 year:** Rubric-based tutor feedback form focusing on five areas of problem solving. Used for weekly formatively assessed tutorial sets.
- **Semester 1:** Weekly problem-solving strategy sheets. Little gain in tutor rubric scores.
  Issues: strategy sheets not read, not enough link to tutorial problems.
- **Semester 2:** Some questions explicitly asked students to implement aspects of problem-solving; "video problems" introduced.

Rubric-based tutor feedback form

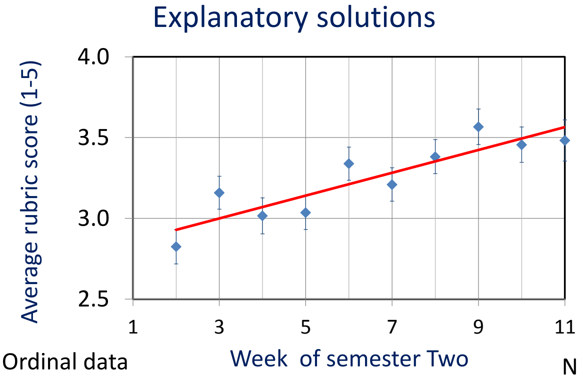
	1	2	3	4	5	
Solutions are not explanatory - just formulas with no text.		X				Explanatory solutions: explanatory text at key points to structure the solution, stating assumptions, defining variables.
No attempt made at qualitative reasoning.			X			Qualitative reasoning used to estimate the answer or possible range of answers prior to any calculation.
No sketches, graphs or diagrams. No other representation than mathematical is used.	X					Sketches, graphs and diagrams where required. These are fully labelled, legible and complete.
No units				X		Units checked to arrive at unit of end result. Units used in intermediate calculations. Units converted to SI units where needed.
No evaluation of work, or of end result.				X		Evaluation of work: discussion whether result makes physical sense. Checking that a formula works for special cases. Checking consistency using units.

Problem-solving strategy sheets

- Simplifying the problem
- **Qualitative reasoning using diagrams**
- Special case analysis
- Unit analysis
- Evaluate the result
- Derive a general formula first
- Derive the result differently



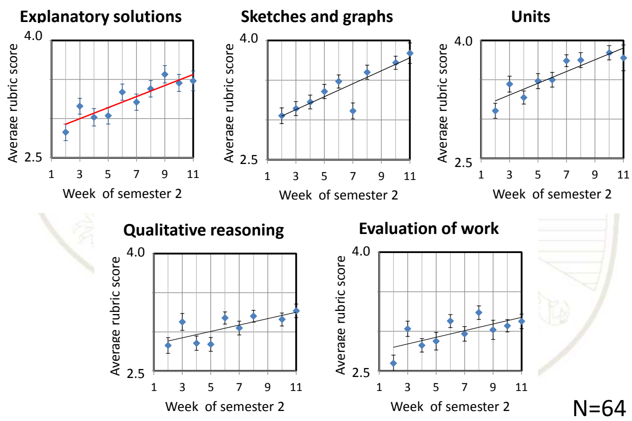
Semester 2 gains in rubric scores



! Ordinal data

N=64

Semester 2 gains in rubric scores



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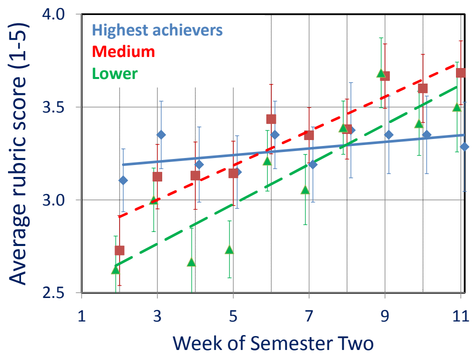
Explanatory solutions



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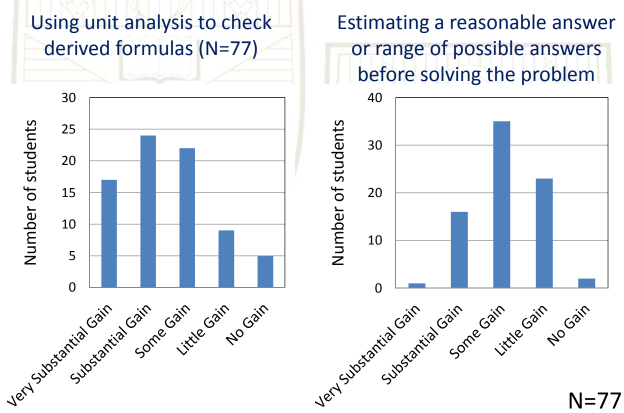
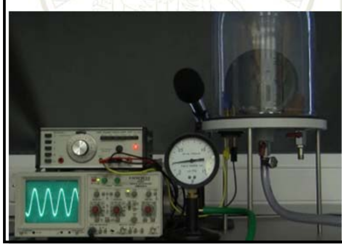
End of year *student-perceived* learning gains



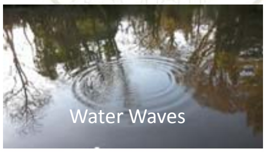
N=77

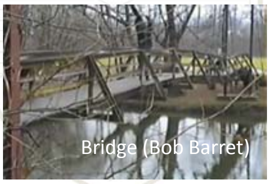
Video Tutorial Problems

- Addressing misconceptions
- "Rich" contexts, on demand
- Qualitative and Quantitative
- Links to "real world"



Classical waves – video problems





All videos available at www.youtube.com/ClassicalWaves

1) Briefly summarize your observations from this video.

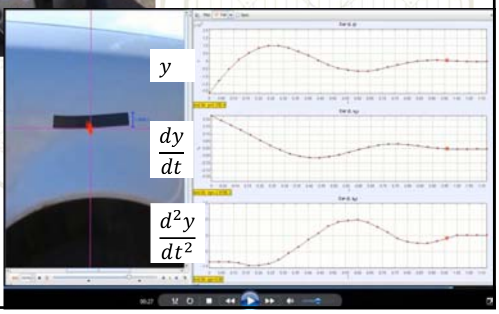
2) From the video, determine the beat frequency using two independent methods. Evaluate your result.

3) Write down an equation for the displacement $s(x,t)$ of the resultant interference wave formed by the two signals.

Videoanalysis problems

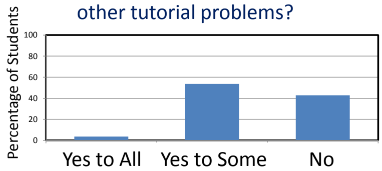
Damped oscillations; analysis using Tracker

www.cabrillo.edu/~dbrown/tracker/

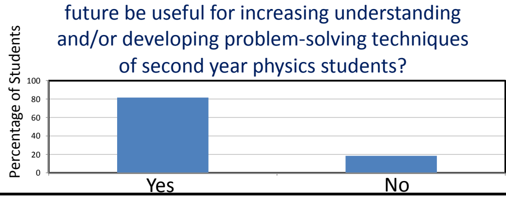


Video Tutorial Problems – Preliminary Evaluation

Did the video problems clarify physics concepts better than the other tutorial problems?



.. do you think that these videos will in the future be useful for increasing understanding and/or developing problem-solving techniques of second year physics students?



N = 64

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  - Problem-based learning projects in level one physics (Antje Kohnle, Tom Brown, Cameron Rae, Bruce Sinclair)

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" A typical physicist's initial strategy is to understand simple systems as completely as possible by constructing physical laws that describe them.
Once this is accomplished, the next step is to add more and more real-world complexity to the system one step at a time."

"Understanding Physics", Cummings et al., p.3

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Level 1 Group Discovery Project

- Three-week long Problem Based Learning (PBL) project, equivalent to 7-lecture course
  - context-rich, real world, ill-defined problem, missing data
  - open-ended or multiple paths
  - group work
  - modified role of tutors as facilitators

Timing

- End of first year
  - consolidation and synthesis of knowledge and skills learnt during the year
  - requires learning new physics and numerical techniques + transferable skills

Project Aims

- Give students the chance to experience working like a real physicist (working in "research mode") and the freedom to come up with their own solution
- Enhance problem-solving skills as well as communication and team-working skills
- Enhanced student ownership, motivation, independent learning, empowerment
- Deeper learning

Group Discovery Project

- Information retrieval session (given by library staff)
- Introductory session: project aims, introductory exercises, students brainstorm the problem and plan next steps
- Workshop session
- Two facilitator sessions, students submit a group action plan prior to each session.
- Group report and oral presentation + questions.

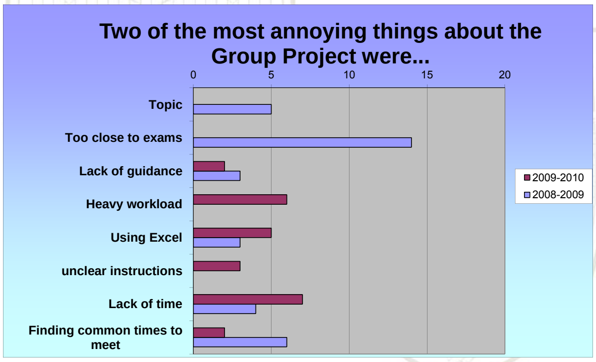
Facilitators

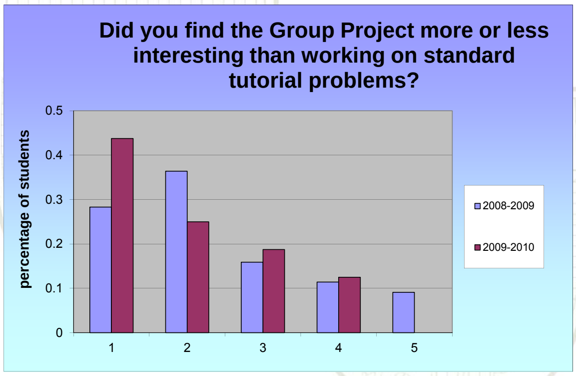
- Facilitator role is decisive
- Facilitator resources: facilitator guide, example solution, literature
- Pre-meeting with facilitators
- Facilitator meeting after the first facilitator session with students

Group Discovery Project - Assessment

- Process and Content assessment
- Individual
  Facilitator sessions (10%)
- Group
  Group action plans (10%)
  Group report (40%)
  Group presentation with demonstration of their simulation and panel question session (40%)
- Group mark moderated by peer assessment using WebPA (http://webpaproject.lboro.ac.uk/)

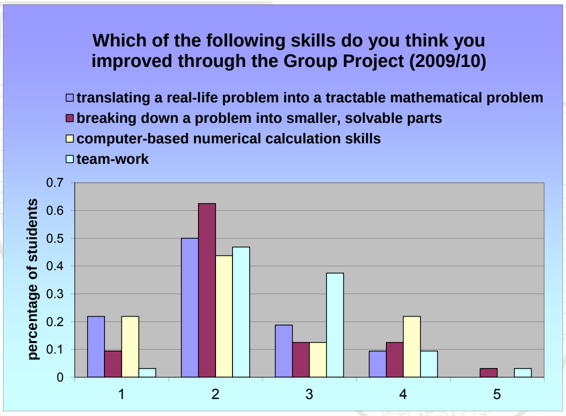
Student survey results





much more interesting

much less interesting



very substantial improvement

no improve-ment at all

Conclusions – Problem-based learning

- Using PBL in first year can give students insight into the research process in terms of creating a simple model, layering of complexity and sanity checks. It may enhance problem-solving and transferable skills
- We have found the following factors important:
  - -timing at the end of the first year; groups with mixed degree intentions and abilities
  - -explaining the reasons for doing this type of project
  - -scaffolding the process (group action plans, timetabling)
  - -careful choice of topic, availability of books/articles at appropriate level
  - -staff facilitators. Pre-meetings and facilitator guide
  - -clear grade descriptors for project report and orals

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Conclusions – Teaching problem-solving

- Strategies made explicit in the tutorial problems.
- Tutor feedback and student perceptions show gains over semester, and more for the less-high achievers. Tutor scores and student perceptions agree. Greater gains in more algorithmic aspects of problem-solving.
- Video problems appreciated.
- Future work: pencasts to illustrate strategies such as qualitative reasoning and evaluation in different contexts; staged problems; more video, more explicit teaching of metacognition.

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Conclusions – Conceptual understanding

- Conceptual understanding decisive for transfer ability.
- Many excellent multimedia resources exist
- Developing effective resources: key is involving students in the development process,evaluation using different methods, revising animations due to evaluation outcomes as an iterative process .
- IOP New Quantum Curriculum project: coming summer 2013.
- Volunteers to trial QuVis animations and suggest improvements / topics for new animations always welcome!

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