How might physics education research help facilitate the computational revolution in education?

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What has computation done for physics?
Physicists Find Elusive Particle Seen as Key to Universe

By DENNIS OVERBYE  JULY 4, 2012

Scientists in Geneva on Wednesday applauded the discovery of a subatomic particle that looks like the Higgs boson. Pool photo by Denis Balibouse

ASBEN, Colo. — Signaling a likely end to one of the longest, most expensive searches in the history of science, physicists said Wednesday that they had
Higgs detected!
Scientists Hear a Second Chirp From Colliding Black Holes

A depiction of two black holes just moments before they collided and merged with each other, releasing energy in the form of gravitational waves.

S. Ossokine, A. Buonanno, T. Dietrich, R. Haas (Max Planck Institute for Gravitational Physics), Simulating eXtreme Spacetime Project
Black hole
Merger
Ringdown!
Computation is how modern science is done.
What has changed in physics education?
1860s-1880s
\[ \nabla \cdot D = \rho \]
\[ \nabla \cdot B = 0 \]
\[ \nabla \times E = -\frac{\partial B}{\partial t} \]
\[ \nabla \times H = J + \frac{\partial D}{\partial t} \]
1900s-1910s
1950s-1960s
What has (really) changed in physics education?
Physics Education Research
Physics Education Research studies:

- student learning and engagement
- pedagogical and curricular impacts
- recruitment and retention of students
- diversity and inclusivity in physics
- faculty practice and decision making
- departmental culture and climate
- national landscapes surrounding physics
Physics Education Research
Standard Model

Physics Education Research Research
Standard Model

The Work of Modern Science

Theory

Experiment

Computation
Physics education requires a computational education
\[
\psi_n = \sum_{m,n} \frac{\langle \psi_m | H | \psi_n \rangle \psi_m}{(E_n - E_m)}, \quad E_n^2 = \sum_{m,n} \frac{\langle \psi_m | H | \psi_n \rangle \langle \psi_n | H | \psi_m \rangle}{E_n - E_m}, \quad E_\pm = \frac{1}{2} [W_{aa} \pm \sqrt{(W_{aa} - W_{bb})^2 + 4W_{ab}^2}] \]
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E_n = \frac{1}{2} [W_{aa} \pm \sqrt{(W_{aa} - W_{bb})^2 + 4W_{ab}^2}] \]
\[ A \frac{d^2 u(x)}{dx^2} = -Bu(x) \]
Where do Bachelor’s grads in physics go?

- Graduate Study: 54%
- Workforce: 46%

2013 & 2014 Graduates, AIP
What are Bachelor’s graduates doing?

- **STEM**: 25%
- **Non-STEM**: 75%

2013 & 2014 Graduates, AIP
Ok, so how do we integrate computation into physics courses?
What do we study?

Sample Research Questions at decreasing “scales”:

• What is the national landscape surrounding computational integration in physics courses?
• How do faculty come into the community of those teaching with computation?
• How are courses designed to incorporate computation given departmental resources and constraints?
• What kind of understanding of computation do students develop in classical mechanics?
• What knowledge and strategies do students use when constructing a shooting method model for energy eigenstates?
• How do students understand a specific line of code (e.g., \( V_{N[i,j]} = (V[i-1,j] + V[i+1,j] + \beta^2(V[i,j-1] + V[i,j+1])) / \text{denom} \))?
from __future__ import division
from visual import *
from visual.graph import *
from physutil import *

# Window setup
scene.width = 1024
scene.height = 760

# Objects
Earth = sphere(pos=vector(0,0,0), radius=6.4e6, material=materials.BlueMarble)
Satellite = sphere(pos=vector(7*Earth.radius, 0, 0), radius=1e6, color=color.red, make_trail=True)

# More window setup
scene.range=12*Earth.radius

# Parameters and Initial conditions
mSatellite = 1
pSatellite = vector(0,5000,0)

# Time and time step
deltat = 1
t = 0
tf = 60*60*24
SatelliteMotionMap = MotionMap(Satellite, tf, 20, markerScale=2000, labelMarkerOrder=False)

#Calculation Loop
while t < tf:
    theta = (7.29e-5) * deltat  # IGNORE THIS LINE
    Earth.rotate(angle=theta, axis=vector(0,0,1), origin=vector(0,0,0))  # IGNORE THIS LINE
    rate(10000)
    Satellite.pos = Satellite.pos + pSatellite/mSatellite*deltat
    SatelliteMotionMap.update(t, pSatellite/mSatellite)
    t = t + deltat
Students solving the Geosynchronous Orbit

Note: video is sped up a bit.
from __future__ import division
from visual import *
from visual.graph import *
from physutil import *

# Window setup
scene.width = 1024
scene.height = 760

# Objects
Earth = sphere(pos=vector(0,0,0), radius=6.4e6, material=mats.BlueMarble)
Satellite = sphere(pos=vector(42164e3, 0, 0), radius=1e6, color=color.red, make_trail=True)

# More window setup
scene.range=12*Earth.radius

# Parameters and Initial conditions
mSatellite = 15e3
pSatellite = mSatellite*vector(0,3073,0)
G = 6.67e-11
mEarth = 5.97e24

# Time and time step
deltat = 1
t = 0
tf = 60*60*24

SatelliteMotionMap = MotionMap(Satellite, tf, 20, markerScale=2000, labelMarkerOrder=False)
FnetMotionMap = MotionMap(Satellite, tf, 20, markerScale=2000, labelMarkerOrder=False)
sepgraph = gcurve(color=color.red)

# Calculation Loop
while t < tf:
    theta = (7.29e-5) * deltat  # IGNORE THIS LINE
    Earth.rotate(angle=theta, axis=vector(0,0,1), origin=vector(0,0,0))  # IGNORE THIS LINE
    Fgrav = -G*mSatellite*mEarth*Satellite.pos/(mag(Satellite.pos)**3)
    Fnet = Fgrav
    Satellite.pos = Satellite.pos + pSatellite/mSatellite*deltat
    pSatellite = pSatellite + Fnet*deltat
    SatelliteMotionMap.update(t, pSatellite/mSatellite)
    FnetMotionMap.update(t, Fnet)
    sepgraph.plot(pos=(t,mag(Satellite.pos)))
    t = t + deltat
How proficient are they?

New Model: Central Force
Assign initial conditions
Compute force
Update velocity

approx. 1300 students
How’d they do?

Caballero, Kohlmyer, Schatz, PRST-PER 8, 020106 (2012)
Finding Commonalities in Students’ Erroneous Programs

Two raters “grade” codes using rubric
High Inter-rater Reliability 91%

Reduce data complexity
Search for similarity using Cluster Analysis

Caballero, Kohlmyer, Schatz, PRST-PER 8, 020106 (2012)
Dominant Errors are Not Syntactic*

80% of students in 5 clusters

<table>
<thead>
<tr>
<th>Dominant Error</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sign Error in Force Calculation</td>
<td>34.6</td>
</tr>
<tr>
<td>Running Code; Error in Initial Conditions</td>
<td>19.8</td>
</tr>
<tr>
<td>Net Force as Scalar</td>
<td>13.3</td>
</tr>
<tr>
<td>Raised Separation Vector to Power</td>
<td>7.6</td>
</tr>
<tr>
<td>Force Calculated Outside Loop</td>
<td>7.1</td>
</tr>
</tbody>
</table>

*Can we separate physics errors from syntactic ones?

Caballero, Kohlmyer, Schatz, PRST-PER 8, 020106 (2012)
Computational Modeling in Physics?
How might students approach computational problems?

w/ Obsniuk & Irving
Interactive Computational Instruction in Physics

pcubed.pa.msu.edu
Irving, Obsniuk, & Caballero, EJP (2017)
Project 3: Geosynchronous Orbit: Part A

The Carver Media Group is planning the launch of a new communications satellite. Elliot Carver (head of Carver Media Group) is concerned about the launch. This is a $200,000,000 endeavor. In particular, he is worried about the orbital speed necessary to maintain the satellite's geosynchronous orbit (and if that depends on the launch mass). You were hired as an engineer on the launch team. Carver has asked that you allay his concerns.

Project 3: Geosynchronous Orbit: Part B

Carver is impressed with your work, but remains unconvinced by your predictions. He has asked you to write a simulation that models the orbit of the satellite. To truly convince Carver, the simulation should include representations of the net force acting on the spacecraft, which has a mass of $15 \times 10^3$ kg. Your simulation should be generalized enough to model other types of orbits including elliptical ones.

Code for Project 3:
- geosync.py
- PhysUtil Module
What do students do when the code doesn’t work?! 

w/ Obsniuk & Irving
from __future__ import division
from visual import *
from visual.graph import *
from physutil import *

# Window setup
scene.width = 1024
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# Objects
Earth = sphere(pos=vector(0,0,0), radius=6.4e6, material=materials.BlueMarble)
Satellite = sphere(pos=vector(42164e3, 0, 0), radius=1e6, color=color.red, make_trail=True)

# More window setup
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    Earth.rotate(angle=theta, axis=vector(0,0,1), origin=vector(0,0,0))
    Fgrav = -G*mSatellite*mEarth*Satellite.pos/(mag(Satellite.pos)**3)
    Fnet = Fgrav

    Satellite.pos = Satellite.pos + pSatellite/mSatellite*deltat
    pSatellite = pSatellite + Fnet*deltat

    SatelliteMotionMap.update(t, pSatellite/mSatellite)
    FnetMotionMap.update(t, Fnet)
    sepgraph.plot(pos=(t,mag(Satellite.pos)))

    t = t + deltat
The group finds a “bug.”
The group begins “debugging.”
“Debugging” leads the group to doing physics.
A case study in debugging

Recognition

Debugging

Resolution

More Strategic

Less Strategic

“...there’s no good reason for it to be moving in that direction...”

“Final momentum equals initial momentum plus net force times delta t. True?”

“Oh, wait...oh god.”

“Did you change it?”

“Maybe, that’s the problem. That we don’t have the initial momentum correct.”

Obsniuk, Irving, Caballero, PERC 2015
from __future__ import division
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    SatelliteMotionMap.update(t, pSatellite/mSatellite)
    FnetMotionMap.update(t, Fnet)
    sepgraph.plot(pos=(t,mag(Satellite.pos)))
    t = t + deltat
F_{grav} = -G \cdot m_{Satellite} \cdot m_{Earth} \cdot \text{Satellite.pos}/(\text{mag(Satellite.pos)}^3)

\vec{F}_{grav} = -G \frac{m_{sat} M_{Earth}}{r^2} \hat{r}
How do students construct the direction vector?

w/ Obsniuk & Irving
<table>
<thead>
<tr>
<th>Step (Sub-Task)</th>
<th>Associated Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construct separation vector between interacting objects</td>
<td>sep = obj2.pos - obj1.pos</td>
</tr>
<tr>
<td>Construct the unit vector</td>
<td>usep = sep/mag(sep)</td>
</tr>
<tr>
<td>Construct the net force vector</td>
<td>Fnet = -G<em>m1</em>m2*usep /mag(sep)**2</td>
</tr>
<tr>
<td>Integrate the net force over time into momentum</td>
<td>obj.p = obj.p + Fnet*dt</td>
</tr>
</tbody>
</table>
Shelley: But ummm wait, hold on, remember this? The uniform circular is equal to the gravity is equal to the net? So we could just do what you did, except instead of using the uniform circular motion equation we use that gravity equation [points to equation].

Joe: Yeah...

Chuck: Okay, yeah, that sounds good.

Shelley: But ummm wait, hold on, remember this? The uniform circular is equal to the gravity is equal to the net? So we could just do what you did, except instead of using the uniform circular motion equation we use that gravity equation [points to equation].

Obsniuk, PhD Thesis (in progress)
Chuck: How do we, okay, how do we define a direction?  
Cody: I don’t know...
Chuck: Isn’t the direction like, okay, so here I’m gonna give like four points on a circle [drawing on whiteboard] so this is the center, and this is a b c and d. Isn’t it always just the position vector of a, so ummm what is it, like satellite dot position minus position dot Earth, and then you can divide that by magnitude?

\[ \vec{\text{F}}_{\text{grav}} = -G \frac{m_{\text{sat}} M_{\text{Earth}}}{r^2} \hat{r} \]
\[ \text{dir} = \frac{\text{sat.pos}}{\text{mag}(\text{sat.pos})} \]
\[ \text{Fnet} = -G m_1 m_2 \text{dir}/R^{**2} \]

Obsniuk, PhD Thesis (in progress)
A stationary star is located at $\langle 1, 3, 0 \rangle \times 10^{14}$ m and a planet moving with a velocity of $\langle 2, -1, 0 \rangle \times 10^3$ m/s is located at a position $\langle -4, 1, 0 \rangle \times 10^{14}$ m. What is the vector pointing from the initial location of the star to the planet?

\[ \vec{r}' = \langle \_\_\_, \_\_\_, \_\_\_ \rangle \]

The Moon orbits the Earth in a roughly circular orbit. To calculate the force the Earth exerts on the Moon, you need to know the direction of the separation unit vector ($\hat{r}$) and the gravitational force unit vector ($\hat{F}$). For locations $A$-$D$, find $\hat{r}$ and $\hat{F}$.

At $A$:

$\hat{r} = \langle \_\_\_, \_\_\_, \_\_\_ \rangle$

$\hat{F} = \langle \_\_\_, \_\_\_, \_\_\_ \rangle$

At $C$:

$\hat{r} = \langle \_\_\_, \_\_\_, \_\_\_ \rangle$

$\hat{F} = \langle \_\_\_, \_\_\_, \_\_\_ \rangle$
How are students taught computation?

w/ Chonacky, Hilborn, & Merner
Surveying the state and implications of computational physics instruction

• Distribute a survey of faculty to investigate the current state of computational physics instruction
• Draw implications for efforts to bolster computational instruction
• Track changes to the state over time

• Sample: 357 departments; 1296 faculty
Do you have experience teaching computation?

- 1 or more faculty with experience teaching computation to undergrads
- 50% or more faculty with experience teaching computation to undergrads

% of Departments (N = 357)

In which courses is computation taught?

![Bar chart showing the percentage of departments offering computation in introductory and advanced physics courses.](https://arxiv.org/abs/1712.07701)

Prevalence of formal programs

- Computational Physics Degree
  - 1 or more (N = 263)
  - 50% or more (N = 195)

- Computational Physics Minor

% of Departments

Prevalence of Instruction

- Computational Homework
- Computational Projects
- Interactive Activities
- Computation on Exams

% of Departments

1 or more (N = 263)
50% or more (N = 195)

Take-Aways

• A majority of faculty report having experience teaching undergraduate students computation

• Computational instruction is more prevalent than in the past\(^1\)

• We are lacking formal computational physics programs

• There is a need to explore interactive methods and assessment techniques for computation

\(^1\)Chonacky and Winch, Am. J. Phys., 2008
Can we learn something more from this data?

w/ Young, Allen, Aiken
Do you have experience teaching computation?

Yes

No
Validation against sequestered data

Confusion matrix, without normalization

<table>
<thead>
<tr>
<th>True label</th>
<th>Predicted label</th>
</tr>
</thead>
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<tr>
<td>Teach Computation</td>
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</tr>
<tr>
<td>Do Not Teach Computation</td>
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</tr>
<tr>
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Young, Allen, Aiken, Caballero, in prep
Important Features

Young, Allen, Aiken, Caballero, in prep
Do you have experience teaching computation?

Young, Allen, Aiken, Caballero, in prep
Do you have experience teaching computation?

Young, Allen, Aiken, Caballero, in prep
Do you have experience teaching computation?

Young, Allen, Aiken, Caballero, in prep
Concerns

• More false classifications when data is biased
  • Solution: Bootstrap when training

• Most important features tend to have more “degrees of freedom”
  • Solution: Alter training algorithm

• Results tied to specific algorithm?
  • Solution: Apply several ML techniques
Other Projects

• How do students debug a program with a visually wrong result? (Oleynik, MSU undergrad)

• How do bioscience students approach modeling predator-prey relationships with computation? (Sand, UiO PhD student)

• What are instructors ideas and approaches to teaching computation in an introductory classroom? (Pawlak, MSU PhD student)

• How do instructor’s ideas relate to their enacted teaching practice when teaching computation in intro physics? (Leary, MSU undergrad)

• What features are predictive of the ways faculty teach computation? (Allen, MSU undergrad)

• What features are predictive of the degree to which faculty teach computation? (Young, MSU PhD student)

• How can computation be used to understand students’ paths in science? (Aiken, UiO PhD student)

• How do faculty come into the community of computational physics teachers? (w/ Irving, MSU faculty)
The MSU Department of Physics and Astronomy voted unanimously in favor of all majors to learn computational physics.*

–April 11, 2017

*Computational science pre-req for major (immediate) + integration of computation in mandatory courses (next 5 yrs.)
PER can help support and facilitate the coming computational revolution

- Research with students
- Research on activities, pedagogy, curricula
- Research with faculty
- Research with departments & larger systems
Thank you!
Questions?
caballero@pa.msu.edu
perl.pa.msu.edu
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