Writing about Numbers: A Project-based Approach to Computational Physics

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PICUP

The purpose of computation is insight, not numbers.

–Richard Hamming, 1962

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Ultimately we want our students to gain wisdom, not merely produce correct answers.

... Why not ask them for it?

Computational Physics I at Syracuse

Audience:

- 15-25 students, mostly second year physics majors
- Less often: computer science, electrical/mechanical/chemical engineering, applied math
- Occasionally: physics PhD students, environmental engineers from SUNY ESF, a music major, an architect...
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Learning goals: students will be able to...

- ... model physical systems in ways suitable for computational attack
- ... make and defend a informed choice of a numerical algorithm to simulate these models
- ... implement these algorithms using tools like those used in professional research[1]
- ... visualize the data from their simulations in ways that contribute to "data storytelling"
- ... validate and interrogate simulation results, since numerics often involve many approximations

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Why not match the students’ activities and assessment directly to these?

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Course design

Main graded work: 7-8 computational projects:

- Done in class (studio environment) + at home with frequent contact
- Usually follow a pattern: "simulate something, examine behavior, learn physics from it"
- 1-3 weeks each

Students submit free-form prose reports on their work:

- Some of the report is guided / answers questions I pose
- ... some of it is free-form, as different students will have different experiences
- They submit their code, but **we do not grade it**
- Focus is on computational **physics**, not computer programming
  - This is a deliberate choice in the learning objectives
  - Other choices make sense too

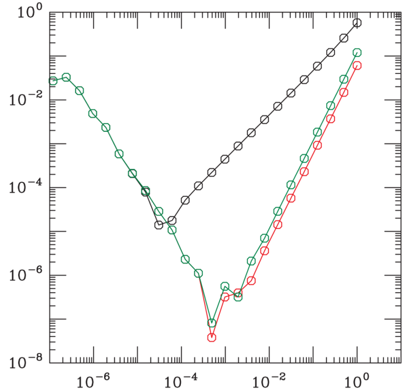
Sample work

The graph of the [error in the] left hand and midpoint rule together looked as I expected it to, with a slope of one, correlating with the order of one, for the left hand rule and a slope of two, with accordance of second order, for the midpoint rule.... With large step sizes there was a pretty big error, as one would expect, which got smaller as the step sizes got smaller. However, when the step sizes got very small, the error suddenly started to rise again. This is because, for each separate bin, the computer makes a rounding error and as the step sizes get very small, there is a very large number of bins contributing to this rounding error causing an increase in the error.

...[The trapezoid rule] behaved very similarly to the midpoint rule, which was expected. The error for the trapezoid rule was a little bit higher, by about a multiple of 2. This is because, when you Taylor expand both integrals you get an approximate error of $\frac{1}{24}h^3 f''$ *for the midpoint rule and* $\frac{-1}{12}h^3 f''$ *for the trapezoid rule, which means the midpoint rule has* $\frac{1}{2}$ *the error.*

Error vs. stepsize:

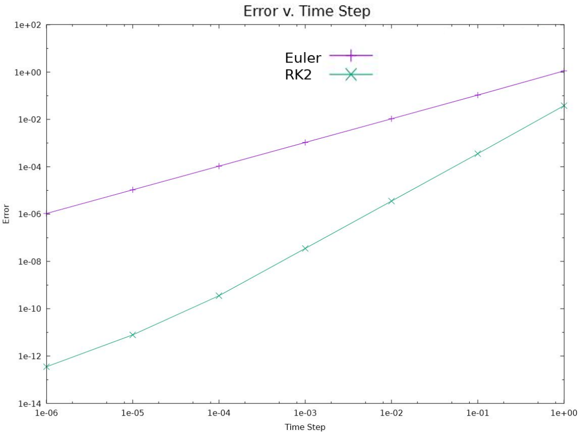
- black = LHR
- green = trapezoid
- red = midpoint



Sample work

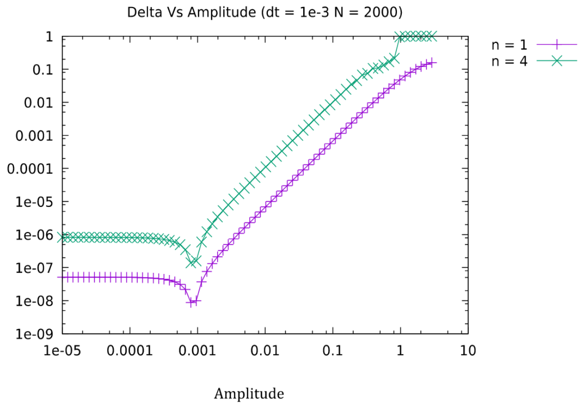
"When using the RK2 method rather than starting at the beginning of the time step to calculate the slope, it is calculated at the point in the center of the time step. This way the slope calculated is closer to the average slope over the interval. This slope is then used to evaluate the function over the entire timestep. To do this the Euler method must be used to first find the value at the midpoint. This process is repeated, using the Euler method to find the midpoint of the interval and then using the slope at the midpoint to evaluate the entire interval, for a certain amount of time to estimate the temperature at that time."

Table 2 [not pictured] shows the raw data from the RK2 method for approximating the temperature. The error here from the actual temperature begins to increase by two orders of magnitude for every one order of magnitude increase in the time step (beginning at the 10^{-6} *time step). Here Graph 8 [to right] shows the error in both methods plotted in a log log plot against the time step used for the approximation.... At the time step 1e-5 the second order behavior of the RK2 method is shown as the curve begins to have a slope twice as steep as the Euler curve.*



Sample work

It is seen that for small amplitudes, the error calculated is constant and insignificant. This tells us that the small angle approximation is being obeyed.... The error rises steadily for both normal modes as the square of the amplitude.... This error is caused by the violation of the small angle approximation. In more mathematical terms, the 2^{nd} *term in the power series expansion of* $\sin(x)$ *can no longer be ignored and hence the small angle approximation fails. If one looks closely at the highest amplitude for the* 1^{st} *normal mode, the error trend changed. Here the* 3^{rd} *term in the expansion can no longer be ignored but as it is of different sign it takes away from the error.*



Strengths

Promotion of synthesis:

- Emphasis on narrative construction requires high-level thinking skills
- "Data storytelling" rather than "the lab manual says to make a graph here"
- Sense-making and mental-model-building are put front and center

Room for flexibility:

- Students can write about what interests them most
- Deadlines can be flexible (easy to give extensions)
- Avoids the rigidity of exams

Student agency:

- Students feel a greater sense of ownership
- Students are aware that this process more closely resembles professional work
- Focus on quality/completion rather than correct answers helps morale

Strengths: diversity and inclusion

The things we're used to thinking about: encouraging underrepresented groups

- Flexible deadlines make accommodating disability/sickness easy
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... and the ones we're not: encouraging diverse intellectual backgrounds

- Writing can inspire students with broader backgrounds
- An anecdote: that musician I mentioned...
- Physics desperately needs these people!

Challenges

Related to assessment:

- Assessment requires qualitative reflection, not a rigid rubric
- Not a problem *per se*: the humanities do this all the time
- Skill/independence required from graders is deeper and broader
- TA's reading for numbers and not insight can pose a problem

Related to implementation:

- **More substantive projects require substantial instructor support**
- Students work odd hours; they need odd-hours help
- Good TA's/LA's are a great help (and learn a lot)