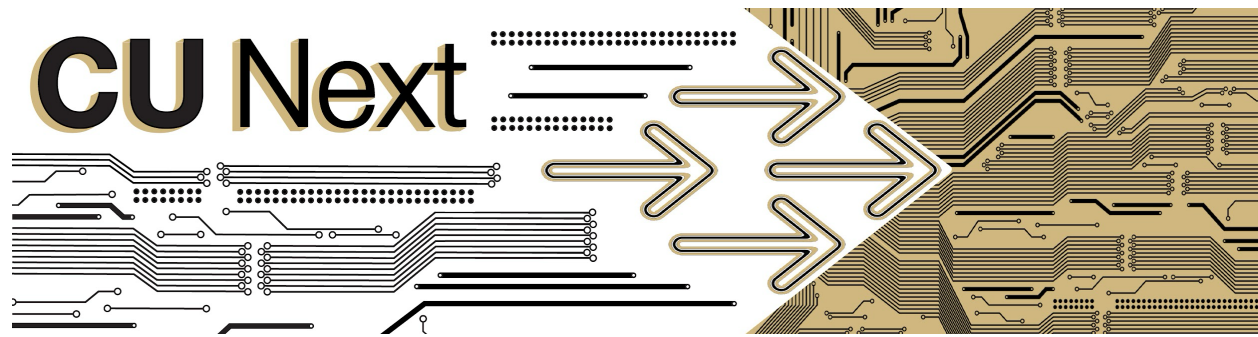


Table of Contents

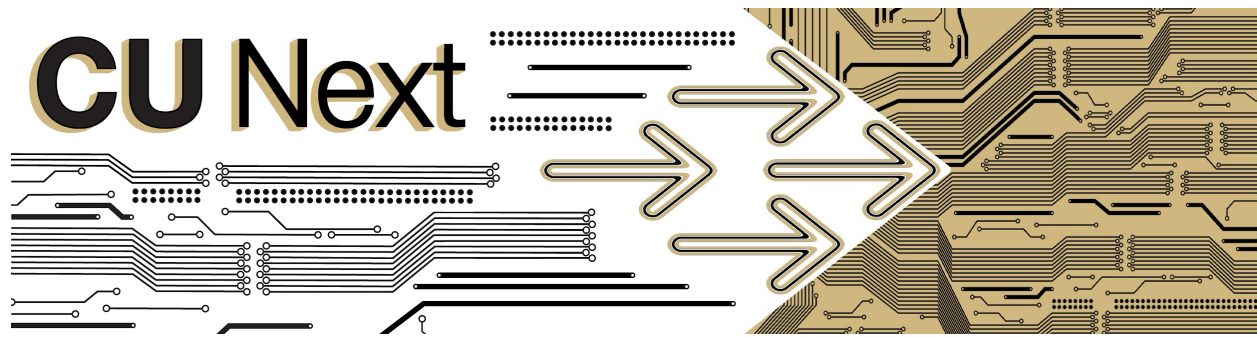
- Cover page page 2
- Description and goals of the project page 3
- Lessons learned page 4
 - Building on responses to the prompts from the three interim reports:
 - What has your team accomplished?
 - What are the challenges you encountered?
 - Did you modify your direction? If yes, in what ways?
 - Did the collaboration evolve, grow, encounter obstacles or challenges?Please provide all examples.
- Results - data and analysis relative to learning outcomes page 5
- Overall conclusions, recommendations, and outcomes page 8
- Appendices page 9



Cover page

Project title: *Interactive Simulations Based on Neural Networks to Teach Undergraduate Fluid Mechanics*

PI: Ankur Gupta, University of Colorado Boulder
Co-PI: Kannan Premnath, University of Colorado Denver



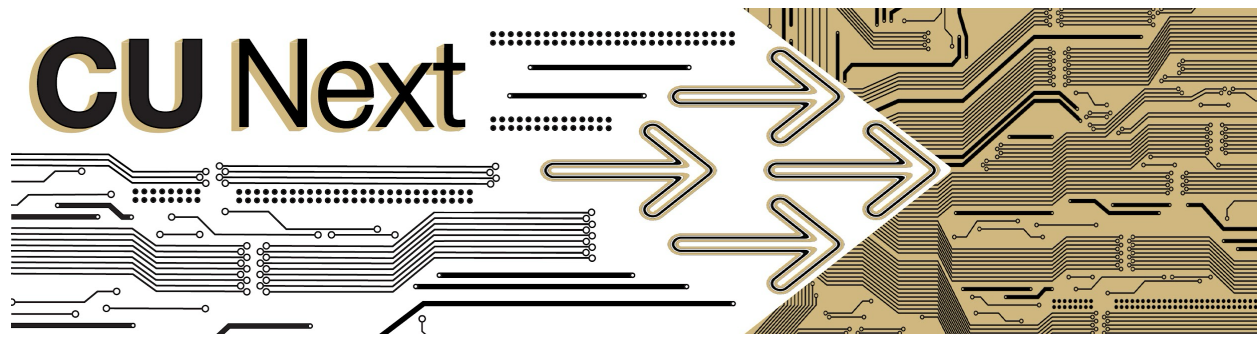
Description of the project and the goals of the project

The idea behind this project was to create a set of tools to better teach quantitative courses using web-based digital simulations. We focus on the course undergraduate fluid mechanics, a core subject of central interest to both chemical and mechanical engineering, and various other branches of engineering, such as civil, environmental, and bioengineering, as well as to science, such as physics and applied mathematics. Studies suggest that teaching fluid mechanics is challenging because the concepts are overly mathematical and abstract, and students often find it difficult to develop an intuitive understanding of concepts. To address the issue, previous attempts have utilized software-based simulations to create interactive exercises to aid student learning. While these attempts did show improved learning, students were required to download and learn new software, thereby creating a barrier for students since they had to learn a new skillset along with learning the usual course material. The software employed is generally designed for special use in industry and research and is not particularly suitable for teaching. Finally, since the software is expensive, it negatively impacts students who are economically less advantaged, or institutes that did not have the access.

This proposal sought to develop computationally efficient yet interactive simulations to teach undergraduate fluid mechanics. The simulations will be designed to perform “digital experiments” and enable students to observe outcomes visually, thus overcoming the abstractness of concepts. In addition, since the simulations will be open source, efficient, and web-based (i.e., no software download required), they will level the playing field for and reduce anxiety related to mathematics. The simulations will free up time for instructors to focus on teaching concepts, rather than performing cumbersome mathematical calculations in the classroom. Consequently, this will impart critical thinking and holistic understanding among students, an important skill set for young engineers to solve challenges in designing products or processes.

As such, the goals of the project included:

- Create interactive simulations that could be played without any software download required
- Test out the interactive simulations in the classroom in both CU Boulder Chemical and Biological Engineering and CU Denver Mechanical Engineering
- Measure the effectiveness of the interactive simulations



Lessons learned

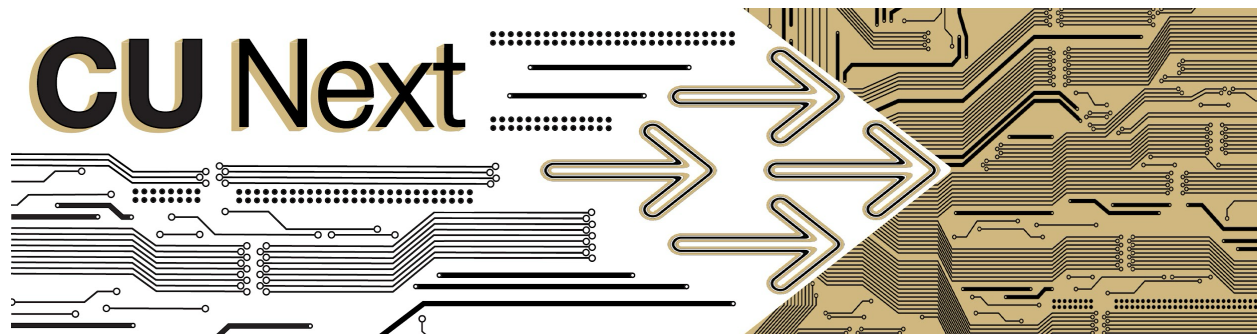
Accomplishments: We successfully executed the project and created 9 such simulations (the links for these simulations are provided in Appendix A1). These simulations included:

- Shape of a drop on different planets
- Buoyancy force -- deconstructed
- Bernoulli's in a network of pipes
- Rankine Tornado Links
- Impinging Jet
- Divergence of velocity
- Shear force direction
- Digital rheometer
- When to open the parachute

We also created a Python code for flow visualization, which was shared with students. We used these simulations in class and conducted pre- and post-clicker questions to measure the improvement in learning. As the project went along, we also integrated these simulations into HW submissions. We collected before and after data across both campuses and found measurable improvement in learning. We also collected qualitative data with an overwhelmingly positive response (see Results below).

Challenges and evolution:

- An evolution in thinking was that some of our initial simulations did not show the code behind the calculations. However, based on student feedback, the future versions started showing the code for interested students.
- Initially, we did not anticipate integrating interactive simulations into HW. However, since the interactive simulations finished reasonably fast during the class, we decided to integrate them into HW.
- There were challenges related to IRB requirements, but both Boulder and Denver campuses were able to obtain it in due time.
- There were also challenges as to how to measure the improvement in understanding within a classroom setting. This is also why HW problems were introduced.
- We were able to work collaboratively across campuses. It was very nice to see similar feedback being obtained in two independent classrooms, further strengthening our confidence in the idea. We did find that different availability of software slightly complicated data collection, but we were able to work through that.
- Finally, when we first conceived the project, we had imagined the use of neural nets to create the simulations. However, as time progressed, we realized that classical computational techniques suffice and are in fact preferred to keep the simulations truly interactive.



Results - Data and analysis relative to learning outcomes

Qualitative analysis: We obtained over 50 qualitative responses from students at the Boulder campus and 44 responses from students at the Denver campus (please see Appendix A2). Across different campuses, some of them have been presented below. Students found that the simulations enhanced their learning and were effective in learning, helped with intuition and visualization, and also helped students appreciate real-world applications.

Denver Campus

1. Enhanced and Effective Learning: Students consistently emphasize that simulations improve conceptual clarity, particularly when paired with equations and problem solving.

- “It helps understand the relation between the variables and how changing one would affect the other.”
- “Honestly... it was the perfect start to understanding a concept.”
- “The simulations are extremely helpful in understanding the content they represent visually.”
- “They provided helpful visualizations that helped me understand better.”

Students also highlight that simulations reduce cognitive load when encountering new material.

- “Some of the things we were asked questions on I had to completely guess before using the app, but after using the app, I got a much better sense of what was going on.”

2. Improved Visualization: Visualization is the dominant theme in Denver feedback, especially for abstract or multi-variable fluid phenomena:

- “As a visual learner, the simulation apps help me understand what the questions are asking.”
- “Being able to see in real time how changing parameters affected flow, force, etc. helped to visualize on top of the mathematical explanations.”
- “The diagrams are helpful visual aids.”
- “Seeing how different variables affect the system is much better than verbally describing it.”

Students repeatedly connect visualization to cause-and-effect reasoning, especially in force balance, vortex flow, and rheology.

3. Real-World Application: Students appreciate simulations as a bridge between theory and engineering relevance.

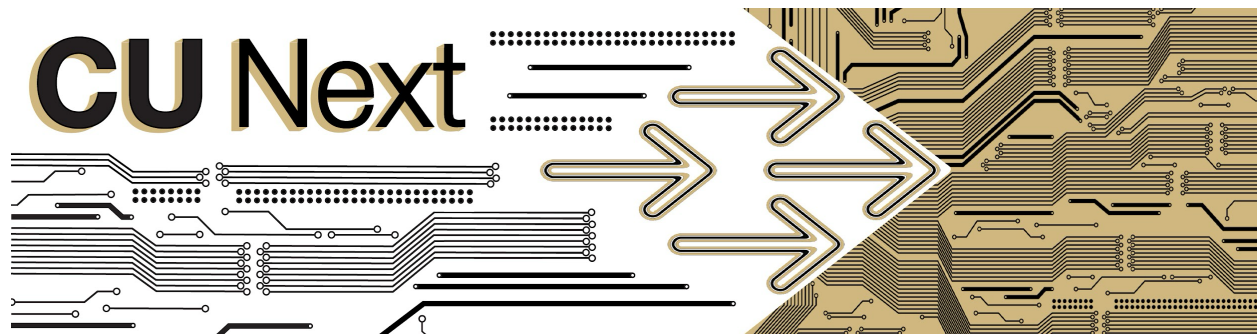
- “They provided the means to see how different variables affect the behavior of fluids or their force interactions with confined solid boundaries.”
- “Visualizing the effects of change helps drive the point across much better than equations alone.”

While some students note usability issues, the pedagogical value is rarely questioned.

Boulder Campus

1. Enhanced and Effective Learning: The feedback is strongly positive, with emphasis on intuition building rather than correctness alone.

- “They helped me gain intuition that was very beneficial when solving conceptual problems.”
- “They’re super helpful when I’m struggling to visualize something.”



- “They help to make sense of answers.”
- “The use of simulations is very helpful.”

A notable pattern at Boulder is that even students who do not use the apps independently still find value when they are demonstrated in class:

- “I never look at the simulations, but I enjoy them when they are demonstrated in class.”
- “I like going over them in class... I haven’t used them by myself yet though.”

2. Improved Visualization: Visualization, especially of vector fields, velocity profiles, and directionality, is repeatedly cited as transformative.

- “They’ve been especially helpful for vector fields for fluid flow and understanding directionality.”
- “Seeing what the graph of velocity vectors would look like was very beneficial.”
- “Flow visualization has been particularly helpful.”

Students identify simulations as complementing (not replacing) analytical work:

- “The simulations are definitely helpful for conceptual understanding.”
- “The graphs during lecture better show velocity plots and what is occurring.”

3. Real-World Application: Students explicitly connect simulations to engineering practice and industry relevance.

- “I appreciate having the opportunity to see how all the equations we derive in lecture are used in industry / the real world.”
- “Application is such a large part of engineering, and I appreciate the simulations’ abilities to show that.”
- “The real-life applications and coding examples are always great to see.”

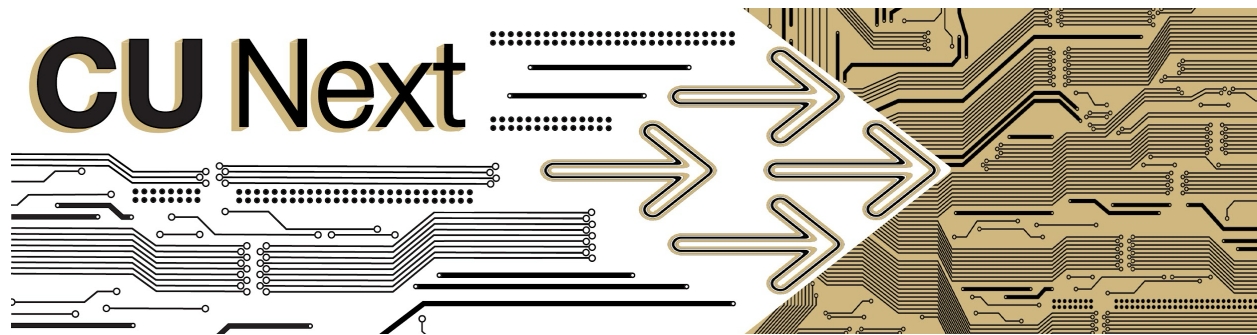
Simulations are also valued as a pedagogical break that maintains engagement:

- “They act as a nice breather during lecture after looking at complex equations.”

Cross-Campus Synthesis: Across both Denver and Boulder, three consistent conclusions emerge: (i) Simulations strengthen intuition, reduce guessing, and support conceptual reasoning, especially for difficult or abstract topics. (ii) Visualization of velocity fields, forces, scaling, and parameter sensitivity is the single most cited benefit across campuses. (iii) Students view simulations as a bridge between equations and engineering reality, reinforcing relevance and motivation.

Quantitative analysis: We analyzed the quantitative data of correct responses before and after the simulations at both Boulder and Denver campuses. We note that the data before and after have been aggregated across multiple implementations (for each simulation) and questions (within each simulation) to consolidate findings.

Boulder campus: Out of the 9 simulations, 7 provided reliable data analysis, which have been presented in the table on the next page. The average participant size at the Boulder campus was 70. Almost all the simulations improved understanding. However, out of the 9 simulations, we note that some simulations were more impactful in boosting the understanding. For instance, the concept of buoyant force, one of the crucial topics in fluid mechanics, saw a considerable improvement.



Denver campus: The data from the Denver campus was aggregated for an average of 12 participants for all the 9 simulations. The Denver campus saw a slightly lower increase in understanding than the Boulder campus. This is not unexpected given the smaller class size and the difference in administration of the two PIs and their styles. Nonetheless, the simulations clearly show an improvement at the Denver campus as well.

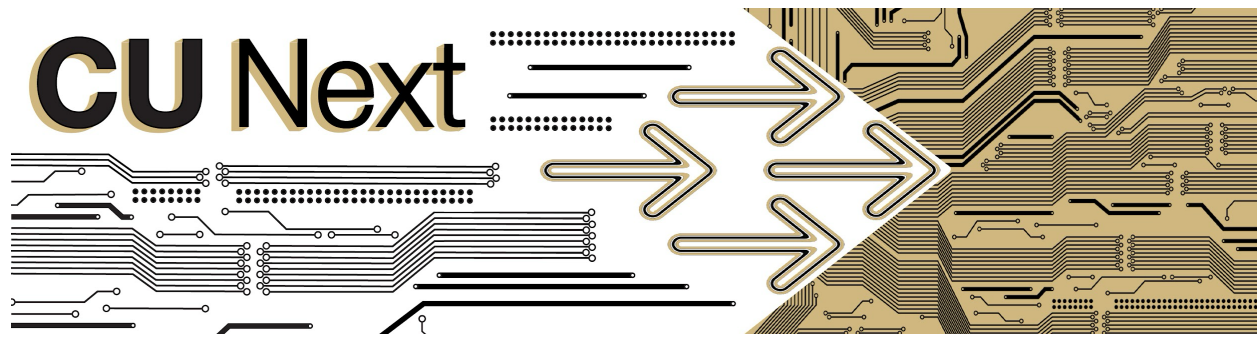
Cross-campus synthesis: The data clearly show that there was a measurable positive effect of the simulations on student understanding. We note that the quantitative numbers were hard to understand in isolation, but we believe that, combined with the qualitative analysis, it clearly shows that the idea that was proposed behind the project is useful.

Secured future funding: PI Gupta secured two additional funding sources to continue this project. First, he obtained an NSF CAREER (\$516,000, Gupta is PI) and NSF IUSE (\$750,000, Gupta is co-PI) to create digital simulations for a broader class of subjects. The NSF IUSE grant goes a step further, where physical experiments are being compared with their digital counterparts. Some of these examples,

which were directly inspired partly by the CU Next award, are provided in Appendix A3. These simulations are more polished because we were able to hire students who are more knowledgeable about website design. Co-PI Kannan is a participant in the NSF IUSE grant and is going to be using some of the simulations and physical experiments in his future classroom to compare the efficacy between the two.

Data Aggregated Over Multiple Implementations and Questions to Consolidate Finding

Boulder campus (average participants: 70)		
simulation	before	after
drop shape	99	99
buoyancy force	39	76
rheometer	45	74
Rankine tornado	10	67
impinging jet	42	62
velocity profile	43	55
shear forces	58	80
Denver campus (average participants: 12)		
simulation	before	after
drop shape	56	75
buoyancy force	51	51
rheometer	45	71
Rankine tornado	44	53
impinging jet	51	78
velocity profiles	48	51
shear forces	54	82
pipe network	41	43
skydiving	58	59



Overall conclusions, recommendations, and outcomes

Conclusions:

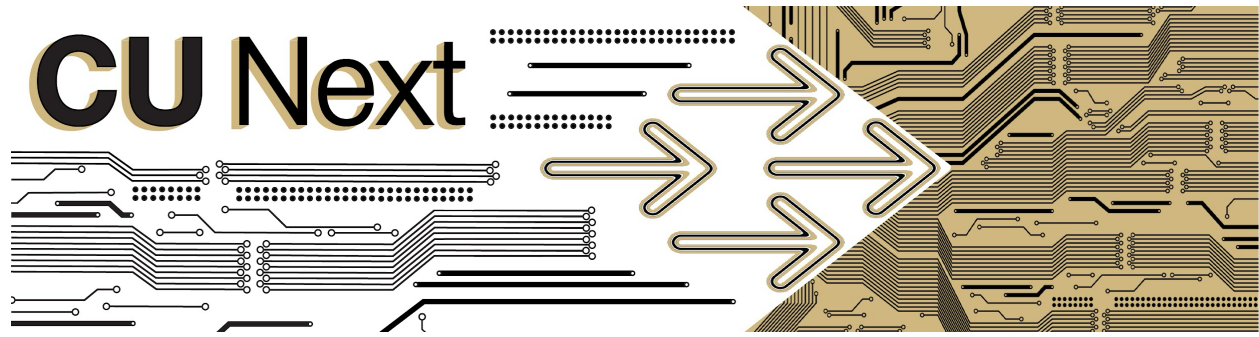
- Interactive simulations were employed in fluid mechanics across both Boulder and Denver campuses.
- Students appreciated the use of interactive simulations and shared that it improved their visualization, intuition, and appreciation for real-life applications.
- Quantitative data suggested a measurable improvement in student learning.

Recommendations:

- Based on the positive outcomes observed, we anticipate that this approach can inform the development of similar instructional tools beyond fluid mechanics. In particular, these instructor-designed simulation tools serve as a vetted, discipline-specific alternative to the increasing reliance on general-purpose AI tools (e.g., large language models) that students now commonly use outside the classroom. While AI tools can be useful, they often bypass the development of physical intuition and may not align with course-specific assumptions or learning goals. The interactive simulations presented here provide students with an accessible, concept-driven resource that reinforces first-principles reasoning and visualization, while remaining fully consistent with the instructor's pedagogy. In this way, the tools complement—not replace—office hours and active instruction, and offer students a trusted, instructor-curated resource for independent learning.

Outcomes:

- Beyond the conclusion, the project led to two new external funding sources from NSF, which included NSF CAREER (\$516,000, Gupta is a PI) and NSF IUSE (\$750,000, Gupta is a co-PI, Premnath is a collaborator).



Appendices

Appendix A1 – Links for simulations and visual compilation

Link to simulations:

1. [Drop shape \(herokuapp\)](#)
2. [Buoyancy force \(Python with code\)](#)
3. [Bernoulli's in a network of pipes \(Python with code\)](#)
4. [Rankine tornado \(herokuapp\)](#)
5. [Impinging jet \(herokuapp\)](#)
6. [Divergence of velocity \(Python with code\)](#)
7. [Shear forces \(herokuapp\)](#)
8. [Digital rheometer \(herokuapp\)](#)
9. [When to open parachute \(Python with code\)](#)

A visual snapshot of the simulations is provided below

Impinging Jet:
Normal force required for deflecting a fluid

$F = 8.96 + 0.2 N$

Shape of a Liquid Drop

Feed for thought: What happens to the drop shape as you vary the contact angle?

Rankine Vortex:
A model for a tornado

Feed for thought: How do the velocity profiles in the center and the outer region differ?

Parallel-Plates Rheometer:
Torque readings for different fluids

Feed for thought: What happens to torque when you decrease the spacing by half only?

Visualization of Velocity Profiles

Code for the Visualization of Velocity Profiles

Hydrostatic Forces on an Object Immersed in Two Fluids

Code for the Hydrostatic Forces on an Object Immersed in Two Fluids

Shear Forces by Fluids on Adjacent Surfaces

Force by the fluid on the top plate

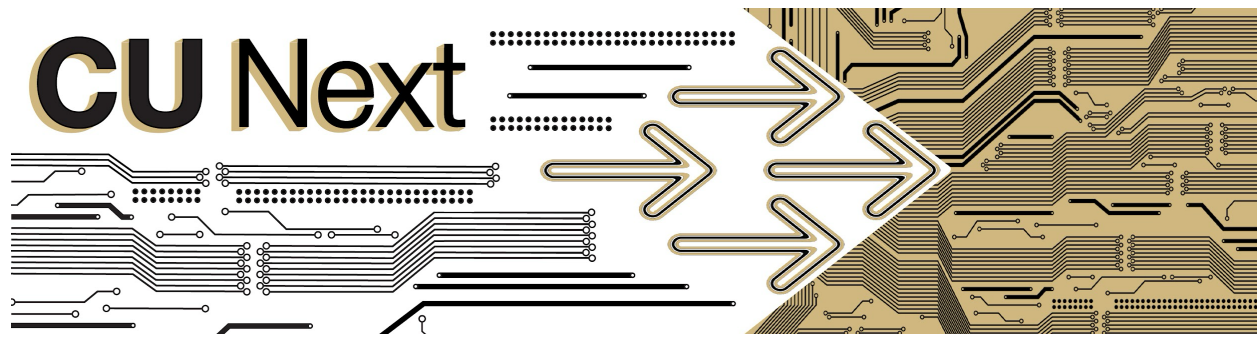
Force by the fluid on the bottom plate

When to Open a Parachute When Skydiving

Code to Determine When to Open a Parachute When Skydiving

Bernoulli's Equation in a Network of Pipes

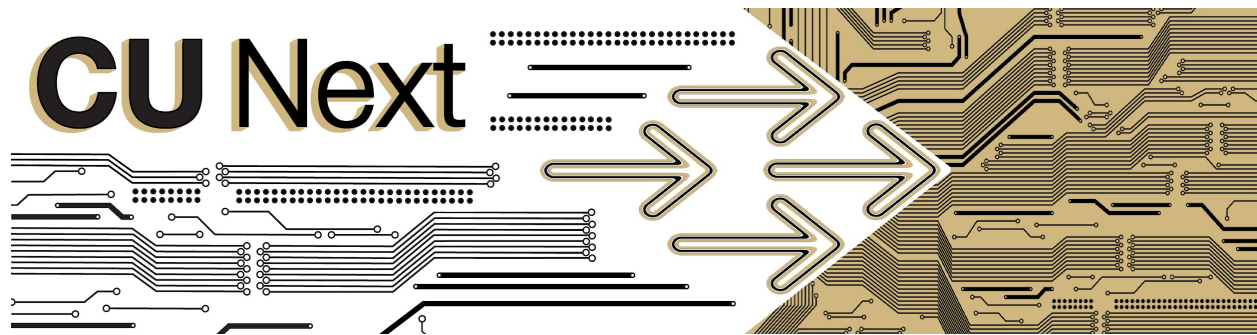
Code for Bernoulli's Equation in a Network of Pipes



Appendix A2 – List of qualitative comments

Denver campus

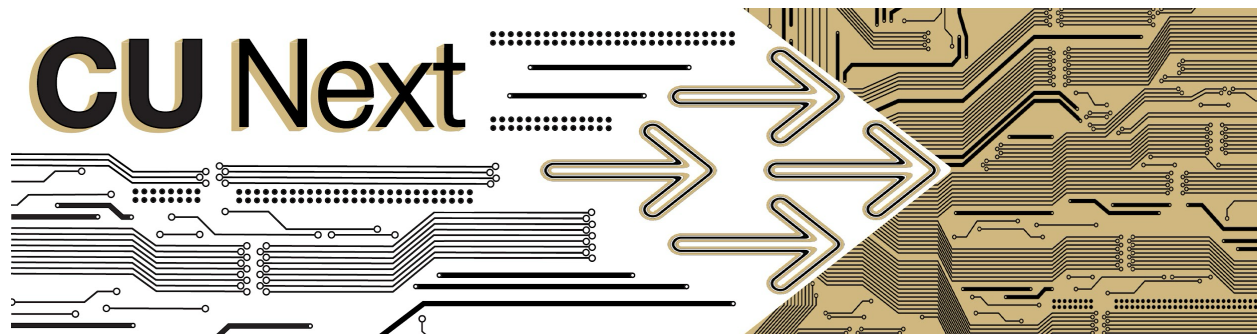
- As a visual learner, the simulation apps help me understand what the questions are asking and how variables effect the simulation (cause and effect)
- I like the fun facts at the left side of the screen
- The diagrams are helpful visual aids.
- I like how it's a good visual way to see how different variables affect the system
- I liked the principle of the apps, being able to visualize how the forces changed when each variable was changed
- I liked being able to see in real time how changing parameters effected flow, force etc. it helped to visualize on top of the mathematical explanations.
- Ability to visualize different fluids paramenters.
- The simulations are extremely helpful in understanding the content the represent visually as well as allow students to play around and simulate different scenarios in the simulation.
- I think the positive aspects of using the simulation apps were the visual imagery. As a visual learner, I found the visual simulation to be more helpful than a mathematical model or formula.
- It helps understand the relation between the variables and how changing one would affect the other. Also, visualizing the effects of the change helps drive the point across much better than verbally describing it.
- difficult to use on devices other than computer/laptop; would be nice to have access to these and use them on our phones/tablets
- if these simulations are related to an equation, it would be helpful to include it so we can see the relationship between the variables of the equation
- the slide bars to changing values work well enough but it would be helpful to enter in a specific value automatically (typing it out than sliding to the number)
- I think it would be more helpful to add more labels to the simulation diagrams as some of them are a bit too simplistic
- It would be helpful to allow manual entry of input values, as the sliders can be difficult to move precisely.
- I think having more designs for different scenarios would be pretty cool
- I'm would say add more variables.
- The only thing is it was hard to slide the bars to the exact number that I wanted.
- This app needs some sort of numerical input to adjust different parameters of the fluids variable.
- I think the neutral aspects of using the simulation apps was the clunkiness.
- The Rankine Vortex freezes frequently on many platforms
- The wording of many of the assessment questions was sometime difficult to understand
- "Solving equation or question make it much easier"
- "I really help me visualize what we were talking about"



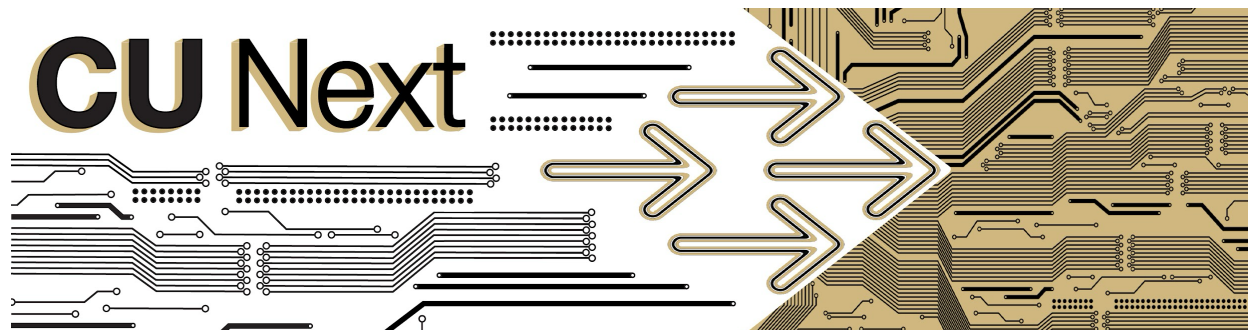
- “most of the time, the simulation apps could be used to answer the questions posed in the polls and helped understanding.”
- “The apps give a visual demonstration of aspects of fluid dynamics that are difficult to understand or imagine.”
- “I like the live feed from the model/picture when you change the input values.”
- “I think it’s a good way to visualize how things work and play with the different variables.”
- “They provided helpful visualizations that helped me understand better”
- “I really enjoyed how it gave the student the ability to control numbers.”
- “Honestly I feel like the apps were quite helpful in learning a basic overall concept.”
- “Sometimes, the apps ran super slow”
- “Sometimes the figures were a little confusing.”
- “Sometimes the app is buggy”
- “The one simulating the vortex had a hard time loading for everyone”
- “It was very helpful to understand the basic concepts of fluids and it was very interactive.”
- “The real time visualizations provide a better example of the concept than static pictures in the book”
- “They simulate really well and helps me understand the problems better.”
- “The visuals are very helpful”
- “I like the visual aspect.”
- “It was hard to use on mobile.”
- “sometimes slow to respond to inputs”
- “Some of the apps crash”
- “It is still an early form of the app”

Boulder campus

- Yes
- I LOVE the simulations! I am very much a visual learner, so I appreciate having the opportunity to see how all the equations we derive in lecture are used in industry/the real world! They also act as a nice breather during lecture itself after looking at complex equations.
- They are great and help visualize things
- i think they are helpful, but i haven’t really found them necessary yet.
- I like these simulations but honestly do not use them to further my understanding, as that is done effectively in lecture and office hours.
- Although I have not used them, I would assume that they are a huge help for visualizing the concepts taught in lecture
- I like the graphs during lecture that better show velocity plots and what is occurring, but I do not use the other simulations
- I think the simulations are very helpful especially when used in class with the given notes
- yes they help a lot in lecture
- I didn’t use them



- I do enjoy the simulations, visualizing things always helps me better understand the concepts
- I appreciate the use of these simulations, as it helps with getting an intuition in regards to some of the equations and math concepts that would be hard to understand otherwise.
- Yes, the real life applications and coding examples are always great to see
- The normal force on the Impinging Jet is hard to read.
- I thought it was super cool! They definitely add to the class
- Yes.
- FIRE!
- I love the simulations, they've been especially helpful when it comes to vector fields for fluid flow and understanding directionality of flow (including today when discussing cartesian vs. polar coordinates).
- These simulations were very helpful in understanding the content.
- They are pretty cool
- I thought they were all very interesting and gave me a real life application to the concepts
- I have no opinion on this.
- I never look at the simulations but I enjoy when they are demonstrated in class.
- Have not used the interactive simulations or seen the need personally but was helpful to see mass balance with vectors in class
- The interactive simulations are very helpful to visualize what is happening; though I do usually only use them when they are shown in class.
- Yes they helped and were really nice to reference for hw problems and such!
- They're super helpful when I'm struggling to visualize something.
- I like going over them in class, I havent used them by myself yet though
- I think the simulations are useful and have helped me work through some problems
- I loved the interactive simulations. They helped me understand concepts better
- I liked when we used them in class and paired with clicker questions.
- They have been particularly helpful for flow visualization, and still somewhat helpful for some of the previous content.
- I liked the simulations and thought they were helpful
- The interactive simulations are great. I say keep doing them.
- I have used some of them to justify answers in my homework which can be very helpful to ease uncertainty of my final answers.
- I did like the interactive simulations. I found they helped me gain intuition that was very beneficial when solving conceptual problems, in particular for what the graph of velocity vectors would look like.
- I enjoy the visualization of important concepts, and I really like the simulations that provide context and application to what we are learning now. Application is such a large part of engineering, and I appreciate the simulations' abilities to show that.
- They're really helpful in visualizing how certain changes affect the system.
- I love these simulations in class, my coding skills are lacking so I struggle to use them sometimes but they're a great way to visualize what we're actually doing.
- Yes, I like them and find them helpful to see what is happening exactly



- I really like them, they help to make sense of answers.
- I like them! The simulations are definitely helpful for conceptual understanding. The coded simulations have helped me less, as usually they are just graphing the information I am able to visualize already.
- I have not used them very much but they are good in lecture
- The use of simulations is very helpful.
- They are very helpful in understanding the material in a different way, and for seeing applications of the concepts.
- I haven't used any simulations so I have no feedback regarding them.
- Diverge, Buoyancy, network of pipes
- I like the simulations when they're used in class to get a more visual understanding of what's going on, but I haven't used them outside of class yet.
- Yes I am a visual learner so these are helpful
- Enjoy the simulations and find them useful

Appendix A3 - Simulations being created as part of NSF-IUSE Grant

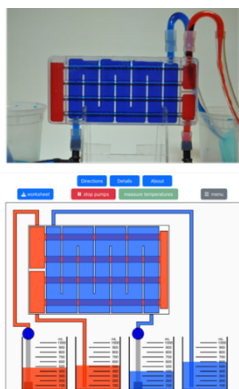


Figure: Comparison of low-cost learning desktop modules and their digital counterpart enables us to test the effectiveness of the two learning approaches. If the effectiveness of learning is similar of both methods, learning by digital simulations could be employed widely.

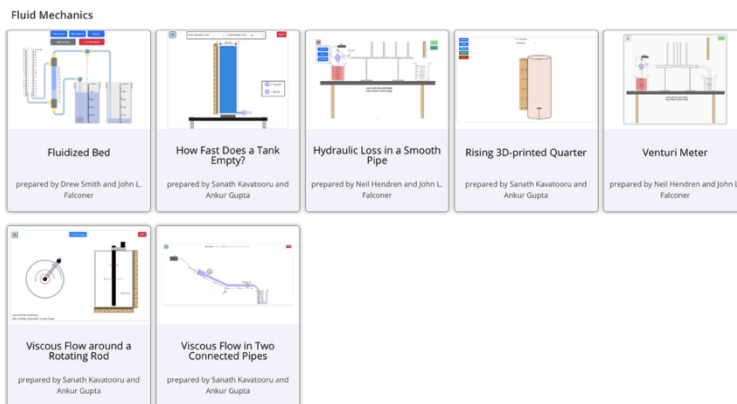


Figure: List of some fluid simulations that came after the CU Next award through the NSF IUSE award. Please view the full list at LearnCheme.com