Physics with Matter-js
Final Paper

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ABSTRACT
There are many interactive and otherwise simulations on the internet regarding physics education. There are many guided courses with visual and interactive aids. There is still room for an open-ended learning environment (OELE) that combines constructionist pedagogy with various forms of scaffolding, found as best practices in review of OELEs. A design and proof-of-concept of an OELE on laws of motion and their scope from simple kinematics to many-body physics is presented here.

ACM Classification Keywords
K.3.1 Computer Uses in Education

Author Keywords
development track; content track; STEM; simulation-based learning; problem-based learning; self-regulated learning; open-ended learning

INTRODUCTION
Constructionist theories have been used to help STEM education for many years founded on the theories of Piaget, extended by Papert, Resnick and others with the development of programs such as Logo, Netlogo, Scratch etc. These are examples of OELEs which could also be in the form of a game, a collaborative exercise, a real-world problem or a simulation. The environment should allow the student to explore freely and establish their own goals [2]. OELEs provide great value and a deeper insight into the subject matter, however they have to be well designed [11][22]. There are many examples of employing constructionist approaches in the research community. Joyner et. al [15] explore a constructionist approach that allows students to compile a simulation based on a conceptual model, one they can repeatedly refine and test. The students were given a very simple learning goal but they still resulted with better causal models. Galan et. al [12] extend the resources discussed in [3] to support user-centric inquiry-based learning (which is in the same vein as constructionism). They allow the user to design experiments based on a set of Java simulations. Other research shows that extra support (scaffolding) in a simulation environment such as: providing background information, guiding hypothesis development, helping conduct experiments, helping interpret data, and helping them regulate the overall learning process is useful for success of a simulation-based learning setup [10]. Providing guidance on steps to take is detrimental to their learning, however experiment prompting and a hypothesis guide is helpful. Further research shows that integrating all the complexity of the phenomena is more effective for student learning [25], as opposed to portraying a simplified form of the concept. Veermans et. al show explicitly detailing the heuristics for the simulation environment results in better self-regulated learning [26]. This is perhaps contradictory, but points out the complexities of research in this field, there might not be a fine balance of control and open-endedness that maximizes learning for all students.

Seymour Papert eloquently on the need of constructionism: "Anything is easy if you can assimilate it to your collection of models. If you can't, anything can be painfully difficult." In the abstract of his book Mindstorms he goes on to espouse how the emotional nature of learning is just as important, and an OELE can provide the flexibility for all students to fall in love with learning, as he did with differential gears [20]. However such individual driven learning requires either a great deal of self-regulation or good design on the part of the instructor. Self-regulated learning (SRL) is when the student exercises some form of metacognition to successfully learn [27]. Students are completely independent and use their pre-existing knowledge to create mental models of the world as provided via a learning environment. The Tinkering Studio is a physical OELE that allows exploring math, science and engineering concepts. However without the right setup, the activities might be fun, but the students will not make meaningful gains in learning, getting stuck in 'unproductive' habits. In [21] the authors provide some key aspects of design that help boost learning:

- Activities that build on prior knowledge/interests, so the student does not ignore it
- Activities should be sufficiently complex to allow for tinkering, so it is not solved instantly, allowing time to reflect on the learning process
- Presence of facilitators to drive interest, help students focus and reflect on their activities

These techniques also translate into virtual OELEs in the form of simulations/games or even a series of tutorials. Intelligent Tutoring Systems may take the role of facilitators.

ACM ISBN None.

DOI: None

The ultimate goal being to foster SRL.

A lot of theoretical groundwork for SRL strategies was laid out in the 1980s. Studies on self-regulation based on self-reporting showed that those with higher SRL abilities performed better in courses. Better self-regulating learners also sought more help from peers, teachers and parents. In the 2000s, due to presence of online learning environments, studies started measuring SRL in new innovative ways [27].

MetaTutor is a time-constrained course on the circulatory system that builds 'scaffolding' via intelligent agents to nudge students to better SRL strategies. MetaTutor additionally collects lots of student data: eye-tracking, audio, electrodermal activity, screen recording and facial expressions. This data is incorporated in the behaviour of the agents. In [5] authors found that students given prompts by the intelligent agents and feedback on their SRL performed better than those without either feedback or both. In a more recent study using MetaTutor [23], the authors found that prior knowledge of the content changed the combination of SRL strategies students pursued, but not necessarily the overall frequency. Prompts and feedback were also found to improve students' SRL abilities [24]. The authors specifically prompted the students to reflect on their learning during the activity, and gave feedback on the level of metacognition in those reflections.

SRL strategies have also found to be beneficial for success in MOOCs [16]. The authors found that goal setting and planning were most indicative of high success in a MOOC, and help seeking was negatively correlated with success. MOOCs are an entirely different environment than the classroom studies in the 1980s, that found help-seeking to be a positive metacognitive trait, thus different results are not unexpected.

The challenges in introducing SRL are bringing some form of control to an OELE. How to incorporate prompts and feedback without destroying the constructionist nature of the environment? The feedback should be clarify good performance, be detailed, provide avenues for improvement, and encourage discussion, among other things [18]. To reiterate the student should be the center of the learning, and not the technology. The student should have a perception of choice, and adequate feedback on the value of these choices, so they can steer from suboptimal learning habits [24]. Social spaces are also useful to foster SRL via sharing of resources and collaborative discussion, which can act as cycles of reflection [17]. Building easy functionality for sharing learning experiences derived form OELEs can facilitate fostering of such communities of practice.

In summary for an OELE to be effective a student has to either be a good self-regulated learner or guided there via scaffolding. Reflection (prompted or otherwise) and feedback from the OELE is necessary to accomplish this.

The literature review has provides with the following keys to a good OELE [10] [25] [24] [21]:

- Good design:
  - allows learner control: eg. ability to switch between difficulty levels
  - allows leveraging learner context: eg. links to external resources on background knowledge
- reflection prompts: eg. prompts asking questions
- feedback on learning: eg. formative assessment
- value:
  - context: how it relates to the real world
  - fun/stimulating/interactive: so they do not lose interest
  - social connection: as it connects to social learning theory

RELATED WORK

A Few Existing Solutions

- https://landgreen.github.io/physics/index.html is a dedicated online course aid for high school / undergraduate physics. This works as a textbook augmented by interactive simulations, not open-ended.
- http://immersivemath.com/ila/index.html is a dedicated course on linear algebra and related topics, essentially a textbook augmented with simulations, not open-ended.
- https://learn.concord.org/ is a repository of numerous simulations that can be incorporated into a course, with varying degrees of interactivity.
- https://www.myphysicslab.com/ closely inspires the proposed design but deals with more advanced topics in physics, and uses only text as scaffolding. These simulations allow for changing the parameters of the simulation.
- [14] is a desktop executable sandbox environment, that is possibly the best contructionist setup for physics education. However it is best used as a tool guided by the instructor.

SOLUTION AND JUSTIFICATION

The proposed solution is thus an OELE containing a physics simulation, visualization of several variables and scaffolding to guide the user to fruitful learning. The simulation will consist of many particles/rigid bodies, where you can visualize the variables as a function of time, visualize the equation, are guided through the possible modifications one webpage at a time, can request prompts/assessment questions, can find a more sophisticated explanation of the concept at hand. While these aspects of a physics education are present on the internet, they are not present in the same place in this form. This allows creation of an OELE that fosters SRL.

This project is meant as an immersive self-contained experience, not necessarily an entire course. This project is designed to anticipate learners who might not be so good at SRL and hopes to expose them to the scope of the laws of motion before necessarily completing any exercises. Hopefully the learner can sufficiently explore to learn to enjoy the laws of motion.

Content and Technology

The OELE consists of a sandbox interactive, implemented using Matter-js [9] (popular physics engine used for video game design), allowing the user to move particles, apply forces and in general see the physics happen. The Dat.GUI controller allows the user to control other parameters of the simulation such as gravity and friction. Two charts are placed adjacent to visualize an equation governing the motion, and variables as they change in real-time, these were implemented using D3. See figure 1 to see the final result. Buttons below the sandbox allow the user to access scaffolding. The rest of the website

was built using CSS and HTML5. The content and concepts covered are listed in more detail in the appendix.
The expectation is that a user will see a graph of the motion, alongside an equation and the motion itself, without making any effort. This would ideally force the user to make connections of the motion with the equation and the relationship between the variables. At best this builds an intuition for the relationship. Several charts are designed to allow for learning specific relationships, but the sandbox is then available for the user to fully explore the possibility space of physics (as limited by the API of course).

Results

Figure 1 shows a frame from the site: https://github.gatech.edu/pages/kjoshi36/physics-js/.

LIMITATIONS AND FUTURE WORK

There are several limitations to this work, mostly surrounding implementation of the complete proposed solution. A few of these are listed on the webpage itself.

TODO

- Allow more functionality in charts
- Build out lesson plan as proposed (seen in appendix)
- Tooltips (for each new chart/concept)
- Assessment (for each section)
- In-depth explanations (for each section)
- Annotate section on external resources
- Build glossary of key terms

Future work apart from implementation involves testing and refining the use cases of such a project, and to determine to what extent it is actually helpful.

CONCLUSION

This is a proof of concept of the proposed solution that aims to bring together many scaffolding techniques to make an OELE for explaining basic physics concepts. Interactivity and visualization of the physics has been implemented but the scaffolding and lesson plan remain, which is a goal for not so future work.

ACKNOWLEDGMENTS

I would like to thank all the students/community in piazza/slack, my peer reviewers, my mentor Cody Oliver and of course Dr. Joyner.

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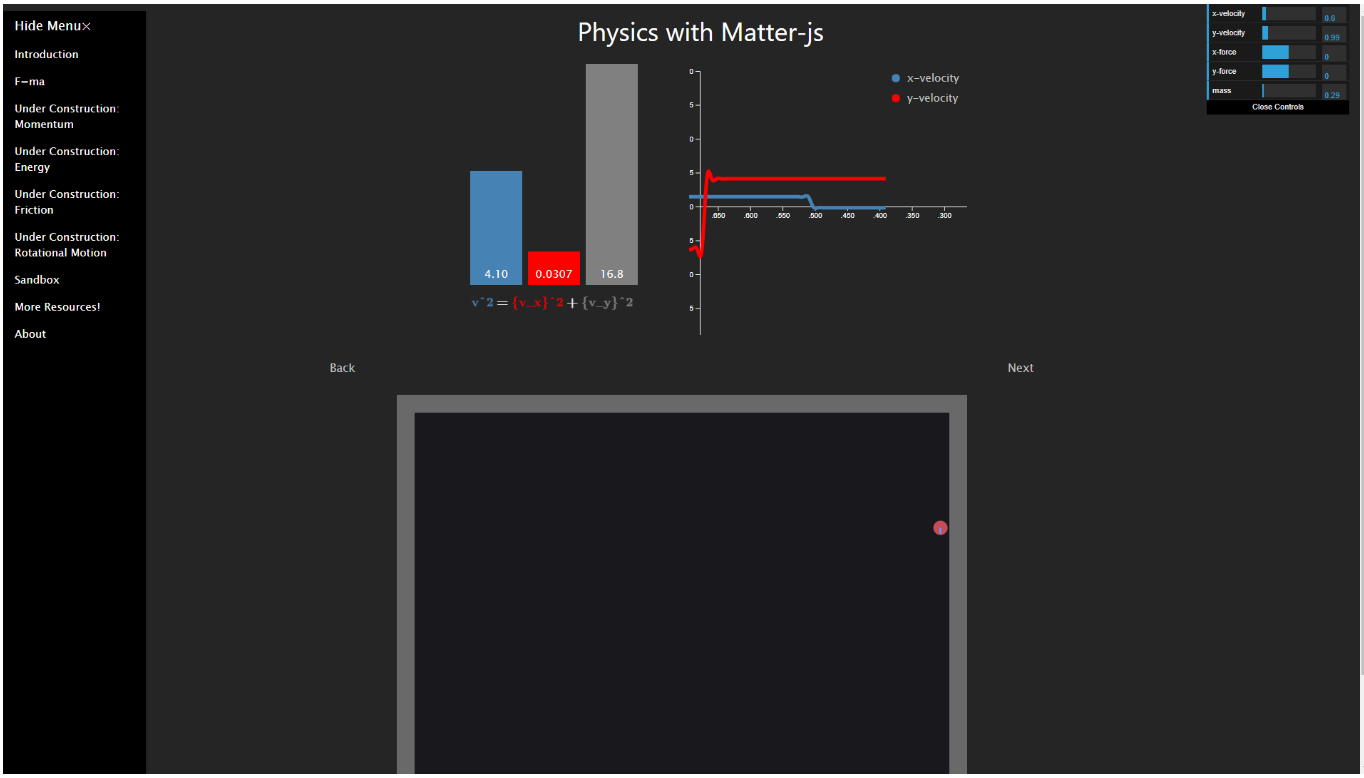

Figure 1. A frame from the site.

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APPENDIX

CONTENT OUTLINE

F=ma

- An object is launched in a random direction with a force vector overlaid on top. User can throw the object around. Equation shows the relative change in the force.
  Equation shown: F=ma (for one particle)
  Graph shown: none
  Options available: none
- Gravity is turned on. User can now vary gravity.
- Multiple particles
  Equation shown: F=ma (for one particle)
  Graph shown: y vs. x position for all particles
  Options available: [number of particles, gravity]
- Chaos: only two particles initialized next to each other with trails activated. "A small change in initial conditions can lead to chaos!"
  Equation shown: None
  Graph shown: y vs. x position for all particles
  Options available: [number of particles]

Momentum

- Two objects are launched at each other.
  Equation shown: p=mv for both objects.
  Graph shown: total momentum and individual momentum
  Options available: none
- Multiple particles
  Equation shown: p=mv for any two objects
  Graph shown: total momentum
  Options available: [number of particles]

Energy section

- Gravity: Object launched in a random direction
  Equation shown: $K = 1/2mv^2$ & $P = mgh$ (for one particle)
  Graph shown: kinetic energy, potential energy and total energy
  Options available: None
- Air Resistance: Particle launched in a random direction
  Equation shown: $K = 1/2mv^2$ & $P = mgh$ (for one particle)
  Graph shown: kinetic energy, potential energy and total energy
  Options available: [air resistance]
- Collisions: two objects are launched at each other
  Equation shown: $K = 1/2mv^2$ & $P = mgh$ (for one particle)
  Graph shown: kinetic energy, potential energy and total energy
  Options available: [Elasticity of collisions]

Friction section

- Two bodies are sitting on top of each other
  Equation shown: none
  Graph shown: force of friction in time
  Options available: none
- Static friction: can vary static friction
  Equation shown: f=s*Fn
  Graph shown: force of friction in time
  Options available: [static friction, add more bodies]
- Inclined plane: an object starts on an inclined plane
  Equation shown: f=s*Fn
  Graph shown: force of friction in time
  Options available: [static friction, add more bodies]

Rotational Motion

- Rolling motion: launch a circle rolling across the bottom
  Equation shown: v=rw
  Graph shown: theta vs. t, w vs. t, v vs. t
  Options available: [change graph, add object]

Full Sandbox

The following options are available:

- particles => circle/square
- friction
- elasticity of collision
- choice of equation => F=ma / v=u+at / p=mv
- show/hide vectors
- choice of graph => one particle / all particles position
- no equation

Glossary

Definitions of key terms
Link to external resources with annotations: doc

About

Credits, list dependencies and link to github source.