i.e.: inquiry in education

Volume 12 | Issue 1 Article 5

2020

Graphene: An Adaptable Engineering Design Project

Ken L. Turner Jr.
University of Dubuque, kturner@dbq.edu

Adam Hoffman
University of Dubuque, AHoffman@dbq.edu

Scott Breitfelder
University of Dubuque, sbreitfelder@dbq.edu

Hayli Wolf
University of Dubuque, hwolf@dbq.edu

Isabella Metcalf
University of Dubuque, imetcalf@dbq.edu

See next page for additional authors

Recommended Citation
Turner, Ken L. Jr.; Hoffman, Adam; Breitfelder, Scott; Wolf, Hayli; Metcalf, Isabella; and Jones, Alexandra. (2020). Graphene: An Adaptable Engineering Design Project. *i.e.: inquiry in education: Vol. 12: Iss. 1, Article 5.*
Retrieved from: https://digitalcommons.nl.edu/ie/vol12/iss1/5

i.e.: inquiry in education is published by the Center for Practitioner Research at the National College of Education, National-Louis University, Chicago, IL.

Graphene: An Adaptable Engineering Design Project

Cover Page Footnote

The authors have no competing financial interests in any component of this study. The authors wish to thank the students, faculty, and administration of University of Dubuque for their enthusiasm and encouragement. We also wish to thank Dr. RPH Chang and Dr. Mathew Hsu at Northwestern University's Materials World Modules for a foundation in Materials Science. The authors also wish to thank the two anonymous reviewers whose suggestions have improved this manuscript.

Authors

Ken L. Turner Jr., Adam Hoffman, Scott Breitfelder, Hayli Wolf, Isabella Metcalf, and Alexandra Jones

Graphene: An Adaptable Engineering Design Project

Ken L. Turner Jr., Adam Hoffman, Scott Breitfelder,
Hayli Wolf, Isabella Metcalf, and Alexandra Jones
University of Dubuque, Dubuque, Iowa, USA

Abstract

Graphene is a novel material with extraordinary promise in various nano-based applications, including increases in strength, conductivity, filtration, and electrical capacity. Graphene can be synthesized and tested in a wide variety of applications in secondary or undergraduate settings. Allowing students to choose their own application and method of testing the graphene they synthesize is an engaging and authentic project based on engineering design and grounded in the tenets of constructivism.
One of the many possible applications, reinforcement of paper mache by graphene, is easily adapted, uses familiar materials and methods, is cheap, and is easy to test. This student-centered project has led to increases in student content knowledge and lab skills. It increases students' confidence in designing their own solutions, analyzing data, and using scientific inquiry and engineering design.

Key words: Graphene, graphite, engineering design, scientific inquiry, science education, STEM, chemistry, physical science, materials science, constructivism, engaged learning, NGSS

Introduction

When teaching science, it is important to teach processes and creativity along with the content. Crafting a lesson that engages the learner with an authentic experience in scientific inquiry and engineering design is a worthy goal with benefits for our students. Scientific inquiry and engineering design are related and integrated but not the same (Heroux, Turner, & Pellegrini, 2010). Both are related to the Next Generation Science Standards (NGSS, 2013), and both are important to K–20 educational practices (Lederman & Lederman, 2013; Padilla & Cooper, 2012).

It is useful to consider the more recent engagement of engineering design (identical in meaning to the older term, technological design) strategies, as it compares with scientific inquiry. Both models are firmly based in the constructivist theory of education. Both are related to NASA's 5E instructional model, Engage, Explore, Explain, Elaborate, and Evaluate (NASA, 2008; see Figure 1).

Figure 1. NASA 5E instructional model

The 5E instructional model is the work of Rodger W. Bybee and originates with the Biological Sciences Curriculum Study in the late 1980's—although it is still extremely relevant for all models of teaching science (Duschl & Bybee, 2014). Bybee himself (1998) presents a compelling argument for inclusion of technological design as a component of science instruction.

Table 1 below may be helpful in comparing and contrasting scientific inquiry and engineering design.

Table 1

A Comparison of Scientific Processes with Technological Design Processes

Steps of the Scientific Process (Inquiry)	**Steps of Technological Design (Problem Solving)**
Observe/question/wonder about a phenomenon	Recognize a need
Develop a researchable question	Create an initial definition of the problem
Conduct a literature search	Gather information from a literature search or from pilot observations
Propose a hypothesis	Revise the problem statement based on the

	new information
Select a research design	Brainstorm possible solutions or iterations (trials)
Identify independent variables, dependent variables, and controls as applicable	Create prototype(s) or model(s)
Plan the methodological details (e.g., sample size, treatment plan, equipment setup, etc.)	Test and assess each solution/prototype/model
Conduct the investigation and collect data	Evaluate the possible solutions and select the most feasible given the design constraints
Analyze and display data	Communicate the results (oral or written) to an audience of stakeholders
Interpret findings	
Draw conclusions to support/not support the hypothesis	
Discuss findings and state implications for future research	
Write the report and publish as appropriate	

Note. See Coryn, Pellegrini, Evergreen, Heroux, & Turner, 2011.

Although most current educators were not explicitly trained in crafting lessons that feature engineering design (Turner, 2015a; Turner, 2015b), the importance of these lessons to our students' learning makes engineering design integration crucial.

Engineering Design

Engineering design is a problem-solving method that scientists and engineers frequently use. As such, it plays a part in many of the authentic practices of scientists and engineers stated in the NGSS. Figure 2 (next page) is taken from the high school level engineering design section from Appendix I of the NGSS. The main headings of "Define Problem," "Develop Solutions," and "Optimize Solutions" are present in the NGSS throughout each level of instruction. Each of these parts is interrelated to the others, and doing any part is supporting the students' experience with engineering design.

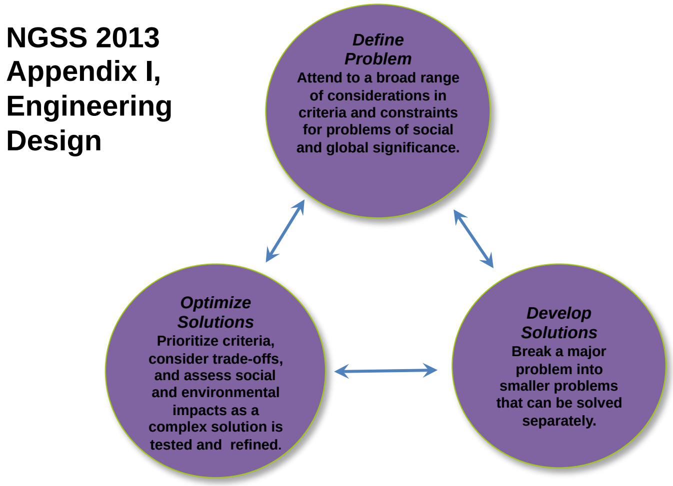


Figure 2. Engineering design from NGSS, Appendix I

In the past, we have crafted engineering design–rich experiences for our students in units focused on microbeads (Hoffman & Turner, 2015), the Gulf of Mexico dead zone (Turner & Hoffman, 2018), and dye-sensitized solar cells (Ho, Hsu, DiPrima, & Offor, 2011). This article will focus on the synthesis and applications of graphene as a topic that teaches chemistry experiences and content, engages learners, and immerses students in the role of scientist and engineer. Teachers can be equipped to design their own engineering design activities with great success (Turner, Kirby, & Bober, 2016). This article may serve as a template for college-level and secondary-level science teachers who might seek to adapt an engaging engineering design activity for their students.

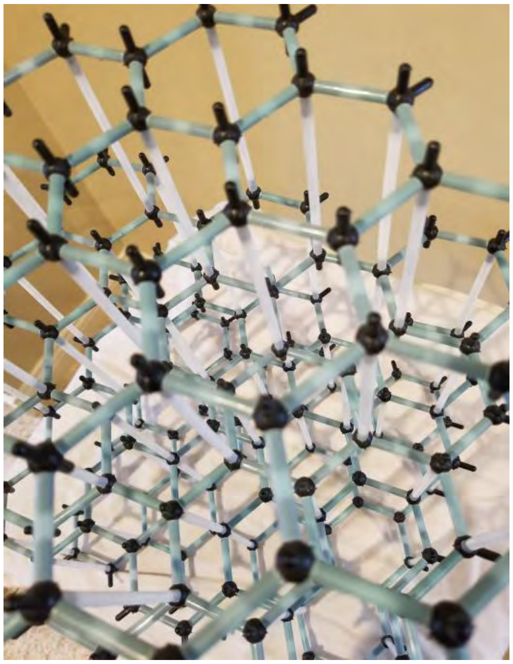


Figure 3. Graphite model. Special thanks to Rock Island high school, Illinois.

Graphene

Graphene is a two-dimensional, covalently bonded, hexagonal arrangement of carbon atoms that shows great promise as an emerging material because of its electrical and mechanical properties. Furthermore, its possible uses in nanoelectronics and nanobuilding blocks coupled with decreases in its production costs may spur even more widespread applications (Li & Kaner, 2008). Although graphene is a cutting-edge material, it can be synthesized (albeit in small quantities and in nano-sized particles) with just some graphite, soap, alcohol, and a blender (Patton et al., 2014; Varrla, et al., 2014). We used the shear exfoliation method of Varrla et al. in producing graphene, using the mechanical shear forces within the turbulence of the solution to break off nano-sized disks of graphene. These discs can then be separated from the bulk graphite by centrifugation.

The following outcomes for this activity are all premised on engineering design and the engaged learner within the pedagogy of constructivism (Kazakçı, A., 2013; Psenka, Kim, Okudan Kremer, Haapala, & Jackson, 2017; Rozov, 2010). There are many ways that graphene can be used within an engineering design setting. For example, the instructor could provide samples of epoxies with differing amounts of graphene added to them. Students could then determine in quantifying differences in the epoxy samples to assess what might make for the strongest and lightest material. That would be a very focused activity on the *optimize* section. Students could build outward from that initial activity to make their own graphene-reinforced epoxy samples or even a prototype phone case, with the improved phone case as the societal need or goal. They could define their goal with the phone case and develop solutions to fit some part of that goal.

Or the instructor could begin by providing a mock letter from a company seeking for the research team (the students) to develop a lighter, stronger phone case. If the lesson were begun in this way, the instructor can assist the students through every stage of the engineering design process, from defining the problem to designing solutions to optimizing solutions and reporting to an authentic stakeholder (the CEO of the phone case company).

Teachers can also be selective in what they provide. Students can still experience various facets of the engineering design process when a teacher chooses some portion for the curricular enhancement. For example, in this research students were directed to use graphene in an application. Their goal was to determine a property of graphene that might enhance a material or product, and they had to be able to make samples that could be tested for that enhancement. Their *defining the problem* was choosing the property of graphene (i.e.: lightweight, greater stiffness, greater strength, electrical capacity, etc.). Students engaged in *developing solutions* as they chose methods of incorporating graphene and testing the material they made for an enhancement because of graphene. Then students could develop solutions by testing for that material against the criteria they selected. After assessing and reporting their outcomes to their classmates, students could *optimize* among the solutions presented. Finally, students had a chance to redefine their problem (their using and testing graphene materials) in the following semester, thus beginning the cycle anew.

Much of this work is a continuing effort to bring engineering design principles to high school and collegiate science courses (Hoffman & Turner, 2015; Turner & Hoffman, 2018). Thus, we sought to create a project that:

- had relevancy for the students
- utilized novel materials and methods
- encouraged creativity by allowing multiple outcomes
- built on student content knowledge from the course and required students to search beyond the course

In order to achieve this goal, we chose a rather open-ended, application-based study of graphene and gave the students the following goals:

> “The overall goal of this project is to engage in the problem-solving approach known as engineering design while you prepare and test graphene. Breaking that overall goal down into simpler goals suggests that you will:
>
> 1) Find background information on the structure, properties, and applications of graphene,
> 2) Synthesize graphene from graphite,
> 3) Separate graphene,
> 4) Use graphene in an application, and
> 5) Test the properties of whatever graphene application you chose.”

Equipped with these goals and a schedule of available lab days, students were able to bring themselves up to date with content knowledge of graphene, synthesize graphene, use graphene in an application, and test their application to determine if the graphene had enhanced the properties of the material in the predicted way.

Allowing such an open-ended lab (meaning, we would accept almost any application of graphene) has great benefits for engaging the students. First and foremost, they are determining the facet of graphene's properties to investigate, the procedure for incorporating graphene into an application, and the method for testing the properties of this graphene-enhanced application. Such freedom of choice in this investigation increases the "buy in" of the students because of its authenticity and relevancy. Having multiple methodologies to achieve a desired goal is a key component of engineering design (Heroux et al., 2010; NGSS, 2013).

Methodology

Students had access to several readings and videos on graphene in the weeks leading up to their first day in the lab. At that first session, students used part of one lab period to synthesize the graphene in a blender. In a second lab session, they used the prepared graphene in an application of their choosing. During a third lab session, students tested whatever application they had made. Finally, during a fourth lab period, students orally presented their work to the rest of the class and completed a lab write-up as an assessment. During their oral reports, students made note of adjustments they would make to their procedures in order to improve the application and its performance. Iterative design is an important part of the engineering design process (NGSS, 2013), and we wanted the students to think critically and analytically about their data and its implications.

Improvement to the Project

During the oral reporting on the graphene project, several student teams presented a common issue. They reported that they failed to get the results they had predicted—and pointed to their lack of experience with graphene. Several teams had good ideas to pursue if they only had a bit more time to work on the project. After considering their comments, we proposed letting the students try to improve on their results in the second semester of the two-semester sequence of General Chemistry. This component of the iterative design process truly allowed for better outcomes, and nearly every student team was able to report improvements in their applications on the second trial. When surveyed at the end of the year, students appreciated and noted the significance this had played in improving their project.

Student teams wrote procedures to make and test graphene-based materials for a variety of applications including: conductivity, filtration, capacitors, strengthening, stiffening, and even hair dye. Greater than 90% of the student teams reported some quantified success in their efforts. For example: the paper conducted, the filter filtered, the capacitor stored energy (Zebarth, 2019), the paper was stronger or stiffer, the concrete was stronger (Breitfelder, 2018), or the hair dye worked. Of the many projects, we will provide details of one team's success in strengthening paper-mache. This project was chosen because the materials are easy to obtain, the procedures are simple, the testing of the material is easy, and it has been replicated by other teams. However, a large portion of the success of the graphene project was due to the student-centered choice of application.

Procedures for Synthesis and Testing of Graphene-Reinforced Paper-Mache Beams

Procedure day 1: Synthesis and isolation of graphene. (Adapted from Varrla et al., 2014.) The following procedure was used in a Ninja blender. It made enough graphene slurry for about sixteen 50-ml centrifuge tubes. The procedure later described requires about 120–150 ml of graphene slurry.

1. Add 120 g of graphite (Fisher #) to 1100 ml de-ionized water in a blender.
2. Add 4–6 g dish soap to 100 ml of de-ionized water in a beaker and mix. Then add 8–10 ml of alcohol.
3. Add the soap/alcohol/water to the graphite/water in the blender.
4. Run the blender on high for a total of 60 minutes; three cycles of 20 minutes on and 5 minutes off.
5. Let the blender sit for at least 15 minutes so that some of the foam settles.
6. Fill 50 ml centrifuge tubes to the 45 ml mark.
7. Centrifuge tubes for two hours.
8. Centrifuge tubes with graphene solution are ready for use by students.

Procedure day 2: Setup.

1. Cut one blue Scott Shop paper towel into three strips measuring 10 cm by 25.7 cm.
2. One strip is control. Set aside.
3. Paint the other strips with the graphene solution, drying in a drying oven at 105˚C between applications for 10 minutes. One strip receives 5 layers, while the other receives 10 layers. (The procedure calls for multiple layers of graphene solution because the solution is very dilute.)
4. Paint control strip with 5 layers of distilled water, drying in kiln at 105˚C between applications for 10 minutes.
5. Using aluminum foil, create a mold for each of the three groups. The

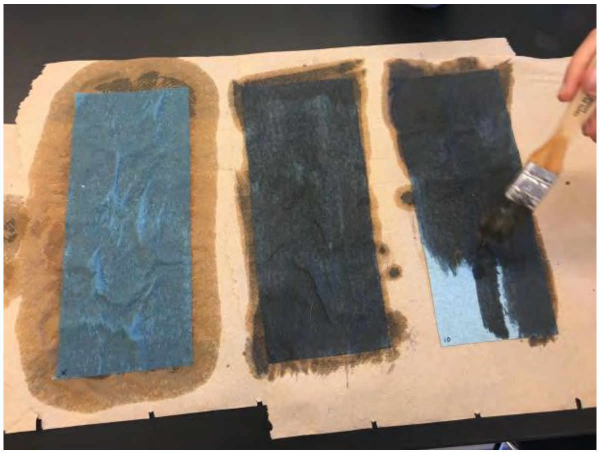


Figure 4. Paper towel samples being painted with graphene and water.

mold should be slightly bigger than the strips and coated with Rain-X (or cooking spray) as a releasing agent.

6. Mix paper-mache paste. (See recipe below.)
7. Paint one layer of paper-mache paste onto one of the paper towel strips. Fold in half so the paper-mache paste is in the middle.
8. Paint another layer of paste on each of the exposed sides of the paper.
9. Using fingers, rub the strip so the layer of paste penetrates the fibers of the paper.
10. Repeat with the other two paper towel strips.
11. Place into mold and set aside, allowing the strips to dry completely before removing the mold (at least 2 days).

Figure 5. Thin-layers of paper-mache applied to the graphene-painted strips.

Paper-Mache Recipe

70 ml Plaster of Paris
70 ml Elmer's Glue-All
20 ml Distilled Water
5 ml Vinegar

1. Mix together Glue-All, distilled water, and vinegar.
2. Stir the plaster of Paris thoroughly into the glue mixture. (Plaster may be divided into thirds and stirred in incrementally.)

Note: Mix immediately prior to painting. Plaster of Paris solution will immediately begin to thicken/ harden.

Procedure day 3: Testing (3-point bend).

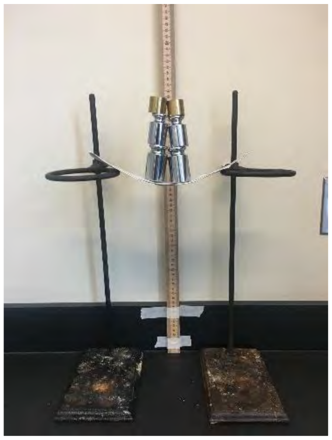
1. Position two ring clamps adjacent to each other, approximately 20 cm apart.
2. Remove each paper-mache beam from its mold and record its mass.
3. Place a paper-mache beam on each ring clamp, forming a bridge.
4. Measure the distance between the table surface and paper-mache beam.
5. Add weights, starting with 100 g and adding additional masses 50 g at a time. Measure the distance between table surface and beam after each application until the beam can no longer support the mass. When the paper folds and falls, that is considered a fail and recorded as the maximum mass.

Data and Observations

Table 2.

Mass Supported and Depression for the Control and Graphene-Reinforced Paper-Mache Beams.

	Total Weight Applied	Depression
Control, No Graphene	900 g	-3.3 cm
Graphene, 5 Layers	1200 g	-4.3 cm
Graphene, 10 Layers	1350 g	-3.5 cm

Control	
	
Graphene, 5 Layers	
	

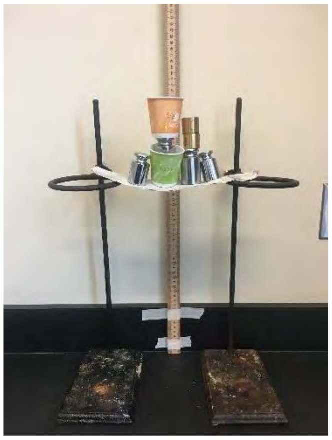
Graphene, 10 Layers	
	

Figure 6. Control and graphene-reinforced beams during testing

Analysis

As shown in Table 2 and Figure 6, the graphene-reinforced paper mache beams held greater mass before failing than the non-graphene control. Furthermore, the beam with ten layers of graphene reinforcement held a greater mass than the beam with five layers of graphene reinforcement. This is consistent with literature that indicates graphene is a strengthening component (Li & Kaner 2008). Each of the student teams replicating this study in 2019 was able to measure similar results. However, there were wide variances from one team to the next over the maximum amount supported before fail. In other words, all groups collected data that showed the graphene-reinforced beams were stronger than their controls, although the strength varied between groups.

We believe that the differences between teams can be attributed to differences between each team making and applying the paper mache. For this reason, we suggest that each team be responsible for making its own control and striving to be consistent in the way that the paper mache is applied. This ensures that the difference between the three beams produced is limited to the amount of graphene. Recording the mass of each paper mache beam should also validate that the increased strength of the paper mache beams is due to the layering of graphene, and not greater amounts of paper mache.

Evidence of Student Engagement

Oral presentations by students, student reports, anonymous student surveys, and anecdotal reports indicate that students were engaged, constructed their own knowledge about the topic, were able to apply concepts from the course, and were able to delve more deeply into the topic because they were able to return to it during the academic year. Pre- and post-project anonymous survey items showed gains in understanding content, such as being able to draw a Lewis diagram of graphene, knowing the hybridization of graphene, and knowing the structural differences between graphene and graphite (Breitfelder, Hoffman, & Turner, 2018). Students also selfreported gains in understanding scientific inquiry and engineering design and confidence in being able to design their own lab experience to find solutions to real-world problems (Breitfelder, Hoffman, & Turner, 2018). Open-ended survey items also provided anecdotal evidence on the *optimize* and redesign portions of the engineering design perspective, such as, “I really liked being able to try something new and see how it would progress in comparison with our previous lab. Thanks for everything! Really enjoyed it all.” and “I think the biggest advantage of doing graphene again is that students can change things about their experiment from last semester to make it better.” Students reported gains in content and skills beyond typical course work with anecdotal evidence, such as, “This project really pushed me to learn so much beyond what was required.”

Conclusion

We have created an innovative, graphene-based lab activity that can be adapted to many classroom settings. Students showed increases in content and science skills as well as engineering and scientific practices, and they enjoyed the activity.

Acknowledgements

The authors have no competing financial interests in any component of this study. The authors wish to thank the students, faculty, and administration of University of Dubuque for their enthusiasm and encouragement. We also wish to thank Dr. RPH Chang and Dr. Mathew Hsu at Northwestern University’s Materials World Modules for a foundation in Materials Science.

The authors also wish to thank the two anonymous reviewers whose suggestions have improved this manuscript.

Dr. Ken Turner is an associate professor of science education at the University of Dubuque; where he teaches General Chemistry, Algebra, Introduction to Research Writing, and Materials Science and Engineering Design. His research interests include intersections of chemistry, education, STEM, and engineering design.

Dr. Adam Hoffman is a professor of environmental chemistry at the University of Dubuque. His research interests include science education, nutrient loading to water bodies, and biogeochemical cycling in aquatic environments.

Scott Breitfelder is an all-science in secondary education major graduating in 2020 from the University of Dubuque. He plans on teaching science at the secondary level after graduation.

Hayli Wolf is currently an undergraduate at University of Dubuque pursuing a double major in biology and environmental science, in addition to her work in 3D facial topography.

Isabella Metcalf is an undergraduate student double majoring in environmental science and biology at the University of Dubuque. Upon graduation in spring 2021, she would like to pursue graduate studies in ecology and evolutionary biology, continuing her passion for research.

Alexandra Jones has varied interests and a passion for research. She plans on graduating in 2022 with a BS in biology from University of Dubuque.

References

Breitfelder, S., Hoffman, A., & Turner, K. L. (2018). Graphene and engineering design in the undergraduate chemistry laboratory: A framework for undergraduate student engagement. *Regional Meeting of the American Chemical Society*, Ames, IA.

Bybee, R. W. (1998). Bridging science and technology. *The Science Teacher, 65*(6), 38–42.

Coryn, C. L. S., Pellegrini, B. J., Evergreen, S. D. H., Heroux, K. H., & Turner, K. (2011). Psychometric properties of the science esteem inventory. *Journal of Materials Education, 33*(3–4), 189–202.

Duschl, R. A. & Bybee, R. W. (2014). Planning and carrying out investigations: An entry to learning and to teacher professional development around NGSS science and engineering practices. *International Journal of STEM Education, 1*, 1–9.

Heroux, K., Turner, K., & Pellegrini, B. (2010). The MWM approach to technological design. *Journal of Materials Education, 32*(5–6), 231–240.

Ho, S., Hsu, M., DiPrima, B., & Offor, M. (2011). *Dye-sensitized solar cells.* Evanston, IL, Northwestern University.

Hoffman, A., & Turner, K. (2015). Microbeads and engineering design in chemistry: No small educational investigation. *Journal of Chemical Education, 92*(4), 742–746.

Kazakçı, A. O. (2013). On the imaginative constructivist nature of design: A theoretical approach. *Research in Engineering Design, 24*, 127–145. doi:10.1007/s00163-012-0150-0

Lederman, N. G., & Lederman, J. S. (2013). Next generation science teacher educators. *Journal of Science Teacher Education, 24,* 929–932.

Li, D., & Kaner, R. B. (2008). Graphene-based materials. *Science. 320*(5880), 1170–1171.

NASA (2008) The 5E instructional model. *NASA eClips*, S. Verstynen (Ed.). Retrieved from https://nasaeclips.arc.nasa.gov/teachertoolbox/the5e

Next Generation Science Standards, NGSS. (2013). Next Generation Science Standards. Retrieved from www.nextgenscience.org

Padilla, M., & Cooper, M. (2012). From the framework to the Next Generation Science Standards: What will it mean for STEM faculty? *Journal of College Science Teaching, 41*(3), 6.

Patton, K. R. et al. (2014). Scalable production of large quantities of defect-free few-layer graphene by shear exfoliation in liquids. *Nature Materials*, *13*, 624–630. doi:10.1038/NMAT3944

Psenka, C. E., Kim, K.-Y., Okudan Kremer, G. E., Haapala, K. R., & Jackson, K. L. (2017). Translating constructionist learning to engineering design education. *Journal of Integrated Design and Process Science 21*(2), 3–20.

Rozov, M. A. (2010). Engineering design in scientific cognition. *Journal of Russian and East European Psychology 48*(6), 45–66.

Turner, K. L., Jr., (2015a). Engineering design case study: Faculty perceptions on preparedness. *Journal of Materials Education, 37*(3–4), 119–136.

Turner, K. L. (2015b). Perceived barriers and solutions: Engineering design implementation (Doctoral dissertation). *Digital Commons at NLU.* Retrieved from http//:digitalcommons.nl.edu/diss/122

Turner, K. L., Jr., & Hoffman, A. R. (2018). Integration, authenticity, and relevancy in college science through engineering design. *Journal of College Science Teaching, 47*(3), 31–35.

Turner, K., Jr., Kirby, M., & Bober, S. (2016). Engineering design for engineering design: Benefits, models, and examples from practice. *i.e.: inquiry in education, 8*(2), Article 5. Retrieved from https://digitalcommons.nl.edu/cgi/viewcontent.cgi?article=1123&context=ie

Varrla, E., Paton, K., Backes, C., Harvey, A., Smith, R., McCauley, J., & Coleman, J. (2014). Turbulence -assisted shear exfoliation of graphene using household detergent and a kitchen blender. *Nanoscale, 6*(20), 11810–11819.

Zebarth, S. K. (2019). Creating graphene powered supercapacitors. *The Colonnade, 2*(1), 1–26. Retrieved from https://digitalud.dbq.edu/ojs/colonnade/article/view/59/60