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Enhancing the Quality of Biologically Inspired Solutions in a Classroom Design Task

Mikayla Dutkiewicz, Embry-Riddle Aeronautical University

Mikayla Dutkiewicz is an undergraduate in Human Factors Engineering at Embry-Riddle Aeronautical University. Her research is centered on exploring the impacts of biologically inspired design on engineering education, particularly how these principles can enhance engineering solutions.

After earning her undergraduate degree, Mikayla plans to pursue a Master's Degree in Human Factors, aiming to continue her research, leveraging human factors principles to further explore the application of biologically inspired design.

Bryan Watson, Embry-Riddle Aeronautical University - Daytona Beach

Bryan Watson, PE earned his Ph.D. at the Georgia Institute of Technology and his B.S. in Systems Engineering at the United States Naval Academy in 2009. After graduating, Bryan joined the nuclear Navy, serving as a submarine officer onboard the U.S.S Louisville and at the Naval Prototype Training Unit from 2009-2017. Significant milestones include earning the Master Training Specialist Certification (the military's highest instructor accreditation), Nuclear Professional Engineer Certification, two Naval Achievement Medals, the Military Outstanding Volunteer Service Medal, and a Naval Commendation Medal for his work troubleshooting and repairing the Moored Training Ship 635's reactor and electrical distribution faults. Following his transition from active duty, Bryan earned his PhD as a member of both the Computation and Advancement of Sustainable Systems Lab, where he developed a new method for distributed system demand estimation, and at the Sustainable Design and Manufacturing lab, where his work focused on increasing System of System resilience. Bryan's work has been published in the Journal of Industrial Ecology, Journal of Mechanical Design, and IEEE's Systems Journal.

At Embry-Riddle, Bryan's current work is focused on investigating the use of biologically inspired design to increase the resilience of modern system. The goal of their work is more reliable services to users, increased user safety, and increased sustainability for connected manufacturing, energy, and infrastructure systems.

Dr. Alexander R. Murphy, Florida Polytechnic University

Dr. Alexander Murphy is currently an Assistant Professor at Florida Polytechnic University. Before this position, he held a Research Associate appointment at the University of Texas at Dallas (UTD). He was awarded an ASEE eFellows fellowship funded by NSF for the postdoctoral research position at UTD. He completed my Ph.D. in Mechanical Engineering in July of 2021 at the Georgia Institute of Technology in Atlanta, Georgia. In Spring of 2018, he was awarded an NSF GRFP fellowship in STEM Education and Learning Research. Dr. Murphy's research areas include engineering design theory, design methodology, design cognition, design education and engineering education. His research involves human-subject studies with both quantitative and qualitative analysis techniques including experiment design, rubric development, inter-rater analysis, and semi-structured and structured interviews. His current research is focused on exploring how system representation affects engineering designer behavior, how trained facilitation impacts the design process, and how experience affects students' approaches to CAD modeling.

Enhancing the Quality of Biologically Inspired Solutions in a Classroom Design Task

ABSTRACT

This study seeks to explore whether exposure to biologically inspired design can enhance the quality of undergraduate student engineering design solutions, with a specific focus on requirement fulfillment. Motivated by a gap in the literature regarding the direct impact of biologically inspired design on student outcomes, this research aims to address the lack of empirical evidence on the effectiveness of biologically inspired design as a pedagogical tool. While existing literature extensively explores the "how" of biologically inspired design implementation, such as frameworks and methodologies, there is limited understanding of its tangible effects on design quality for novice designers (students). This study fills this gap by investigating whether biologically inspired design principles lead to more innovative and effective solutions, enhancing creativity, sustainability, and problem-solving skills. Using a two-condition experimental design, participants were exposed to either a biologically inspired design intervention or a control video before completing a design challenge. The results revealed mixed findings: while early integration of biologically inspired design correlated with better alignment to design requirements, the presence of biologically inspired design elements in solutions was negatively associated with rubric scores and the use of biologically inspired design priming did not correlate with design performance. Ultimately, this research contributes to the growing body of knowledge on biologically inspired design in engineering education, emphasizing its potential to improve student design while identifying key areas for further study and improvement.

1 INTRODUCTION & BACKGROUND

Biologically inspired design (BID), which draws on nature's principles to inspire innovative engineering solutions, has gained attention across various disciplines due to its ability to harness the efficiency, adaptability, and resilience found in biological systems. By studying natural phenomena, engineers and designers can develop solutions that are innovative, sustainable, and ecologically responsible. For instance, BID has been lauded for its potential to address pressing sustainability challenges by offering eco-friendly alternatives to traditional design methods, such as reducing material waste, optimizing energy usage, and enhancing product longevity [1][2].

The practical applications of BID are diverse. In robotics, animal locomotion has inspired advancements in mobility and flexibility, as exemplified by soft-robotic systems mimicking the movement of rays and other aquatic creatures [3], [4] Other researchers have developed robotic jumping mechanisms inspired by a dog's legs improving jumping performance [5]. Similarly, in materials science, structures modeled after biological entities like leaves or shells have led to breakthroughs in strength, flexibility, and efficiency[6]. Examples include self-repairing concrete inspired by human bones and aerodynamic ceiling fans based on the structure of Sycamore seedpods [7]. In addition to real-world applications, tools such as IDEA-INSPIRE and AskNature allow engineers to systematically explore biological analogies. These tools enhance ideation by providing structured approaches to accessing and applying biological insight[8]

Georga tech has made multiple efforts to integrate Biologically inspired design (BID) early into educational curricula. The BIRDEE (Biologically Inspired for Engineering Education) program at Georgia Tech introduces high school students to engineering through bio-inspired design, aiming to increase student engagement and their understanding of the connection of the natural world and engineering [9], [10]. The program provides curricula tailored for sophomores, juniors, and seniors, aiming to inspire more students to pursue engineering fields [11]. Furthermore, the Georgia Tech's course "Enhancing Innovation Through Biologically Inspired Design" provides practical training in BID for upper-level undergraduate students majoring in engineering and biology. This course includes BID lectures, design lectures, found object exercises, quantitative assessments, analogy exercises, research assignments, interdisciplinary collaboration, mentorship, and idea journals. It aims to develop novel techniques for creative design, interdisciplinary communication skills, and the application of existing technical knowledge to new disciplines. The course culminates in a group project where students produce a conceptual design incorporating biological principles, encouraging a deeper understanding of both biology and engineering [12].

While established instructional tools such as TRIZ, functional decomposition, and AskNature are often integrated into formal BID teaching, this study intentionally adopted a more basic approach. Rather than delivering a full structured intervention, we provided students with minimal priming, using brief conceptual prompts and examples, to examine if even a brief exposure can activate biologically inspired thinking.

The textbook *Biomimetics: Nature-Based Innovation*, where Chapter 10, "Biologically Inspired Design: A Tool for Interdisciplinary Education," outlines a comprehensive course structure that includes lectures, exercises, and interdisciplinary collaboration to bridge the gap between biology and engineering, encouraging creativity and innovation [13], [14]. Another textbook, *Biologically Inspired Design: Computational Methods and Tools*, features Chapter 7, "Adaptive Evolution of Teaching Practices in Biologically Inspired Design," which discusses the implementation and evolution of a BID course at Georgia Tech, highlighting its success in enhancing students' understanding of both biology and engineering [15], [16]. These textbooks represent interest in the development and implementation of BID educational tools for the classroom. Incorporating BID content can make learning more exciting and prepare students to innovate in sustainable ways inspired by nature, such as solving real-world problems using nature-inspired solutions and engaging in hands-on projects [17].

Despite its growing popularity, there remains a notable gap in empirical research assessing the direct impact of biologically inspired design on engineering education, particularly in relation to the quality and functionality of student-generated design solutions. While BID has been increasingly integrated into educational settings, most research has focused on the methodologies and implementation or the "how-to" rather than the impact on the student design process. This lack of evidence leaves a critical question unanswered: Does incorporating BID into engineering curricula lead to measurable improvements in the quality of engineering solutions, or does it just offer interdisciplinary skills and conceptual benefits?

Several studies have explored frameworks and methodologies for implementing BID, offering insights into its potential but falling short of evaluating its effects on student outcomes. For instance, [18] propose metrics such as novelty, usefulness, and completeness to assess the effectiveness of ideation processes in BID, yet they do not directly address how these metrics translate into improved quality or functionality in student solutions. Similarly, [19] emphasizes the importance of interdisciplinary collaboration and structured approaches to teaching BID, but they do not provide empirical evidence demonstrating that these strategies result in better engineering designs [19].

A study found that hybrid approaches to biologically inspired design (BID), combining intuitive and directed methodologies, can enhance design processes. However, the application of these approaches in classroom settings remains underexplored [[2]. Another study discussed how motivations for engaging in BID, such as sustainability and innovation, can drive success in projects. However, it stopped short of evaluating whether these motivations influence the quality of solutions in educational contexts[1]. Similarly, research advocated for using structured frameworks, such as the Structure-Function-Mechanism (SFM) approach, to teach BID effectively. This study primarily focused on the teaching process rather than the outcomes of student-generated designs[20]. While other studies showcase the broader potential of BID in innovation and sustainability, they do not address its specific impacts on educational outcomes[7], [21]

Understanding whether and how BID frameworks enhance the quality of student solutions is essential for validating its role as an effective pedagogical tool. Such research would provide educators with evidence-based strategies for integrating BID into their curricula, ensuring that its potential benefits, such as promoting innovation, improving problem-solving skills, and encouraging sustainable design practices, translate into tangible improvements in student-generated solutions. This gap in the literature highlights the need for more focused research to bridge the divide between the advantages of BID and its practical use in engineering education. In this study, the BID priming was intentionally minimal, designed to explore if even a brief exposure will activate biologically inspired thinking in student designers. By addressing this gap, future studies can contribute to a more comprehensive understanding of BID's role in shaping the next generation of engineers and designers. In this study, it is hypothesized that *if undergraduate engineering students are primed with information about biologically inspired design, they will outperform students who were not primed in a design challenge (as measured by requirement fulfillment) because the BID priming will enhance solution quality.*

2 METHODS

2.1 Participants and University Context

Participants in this study were 26 undergraduate students enrolled in three sections of Graphical Communications class. The course introduces students to technical drawing, CAD, geometric constructions, blueprint reading, and 3D visualization, emphasizing skills needed for effective engineering communication. This introductory course is primarily taken by first- and second-year students. The participants were engineering students, with 22 studying aerospace engineering, 2 in mechanical engineering, and 2 in engineering physics.

2.2 Study Overview and Design

This study seeks to examine the hypothesis by analyzing the influence of BID on the quality of solutions generated in a classroom design task based on requirement fulfillment. By evaluating student projects through established metrics and frameworks, this research aims to determine whether BID can serve as an effective pedagogical tool for enhancing engineering education.

The study will implement two conditions for participants:

> **Condition 1**: Participants will be shown a brief video on biologically inspired design, then asked to complete a design challenge based on a natural language script that has the requirements of the design challenge. The BID intervention was intentionally limited in scope and consisted solely of a short video introducing BID through a few real-world examples. Upon completion of the challenge, they will be asked to go back and label any bio-inspired design elements if there are any.
>
> **Condition 2**: Participants will be shown a control video that does not mention biologically inspired design, then asked to complete the same design challenge. They will also be asked to label any bio-inspired design elements upon completion.

The study will compare the solutions of the two groups to highlight the possible impacts of biologically inspired design implementation in engineering education. By examining the quality and functionality of the student-generated solutions, this research aims to provide empirical evidence on the effectiveness of BID as a pedagogical tool in improving student designs (as measured by meeting requirement fulfillment).

2.3 Study Procedure

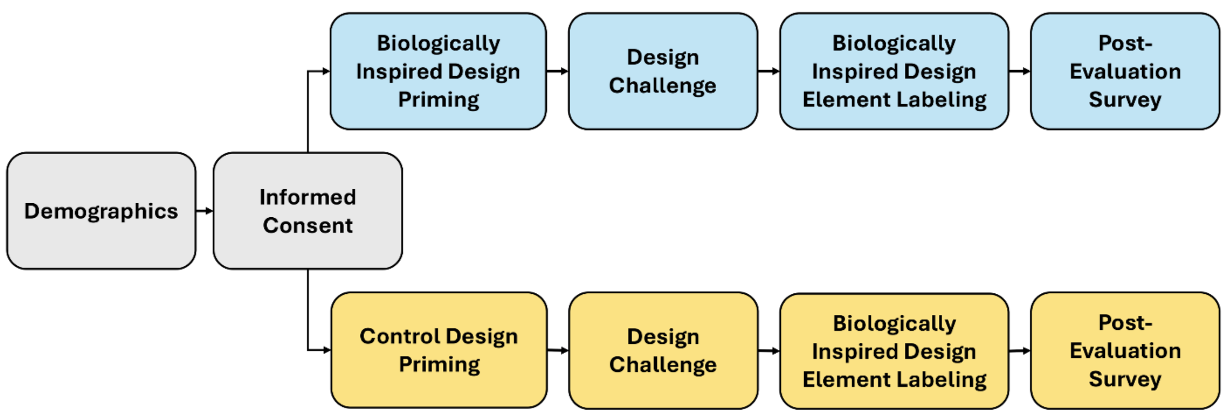


Figure 1: Experiment Methodology Flowchart

The study began with a 5-minute session for informed consent and demographic collection. During this time, participants were briefed on the study, provided informed consent, and completed a demographics form. Students were given the opportunity to keep a copy of the informed consent for their personal records. The demographic form collected information on age, gender identity, major, and year in school for demographic analysis.

Following the collection of demographic information and informed consent, participants underwent a 5-minute were assigned to their respective conditions. Participants in Condition 1 watched a video on biologically inspired design, while those in Condition 2 viewed a control video. The videos included a short explanation of BID and its practical applications (Condition 1) or the history of sketching (Condition 2). The history of sketching was chosen as the control video as it provides a neutral topic that was not expected to influence participants' design thinking or creativity as related to biologically inspired design. A summary of the video presentations can be seen in Appendix C and Appendix D.

After the educational intervention, participants engage in a 15-minute design challenge. Participants were tasked with creating a remotely controlled underwater system for trash collection. The challenge is presented through a script in natural language (Appendix A), detailing specific requirements. For example:

> *"Um… well, the main goal is to collect different types of trash, like microplastics and larger debris, without harming the ocean floor. We do not want any safety issues, so it would be amazing if it could be remotely controlled and monitored and powered, since the ocean is so deep and dark."*

This excerpt from the script includes several requirements: the design should collect both small and large types of trash, ensure user safety, be remotely controlled and monitored, and be capable of operating in the deep, dark ocean. The challenge was presented through a script in natural language to ensure clarity and accessibility for all participants, regardless of their technical background. Using natural language helps to enhance understanding by making the requirements more understandable and relatable, reducing the cognitive load on participants[22].

Examining the design solutions based on requirement fulfillment gives a more quantitative measure based on whether a requirement was met or not, making the evaluation process less subjective. This approach enhances comparability by using user specified requirements, making it clear which solutions are more effective in meeting the given challenges. Lastly, measurable outcomes provide concrete data that can be analyzed statistically, helping to draw more in-depth conclusions about the impact of BID on the quality of student-generated solutions [23], [24]. By combining natural language scripts with quantitative requirement fulfillment, the study aims to balance clarity and creativity with objective, measurable outcomes.

During the design challenge, participants were instructed to use a black pen to create their design, identify components, and label them, while also writing descriptions of the functionality of each design aspect. Once the design challenge was completed, the black pens were collected, and each participant was given a green pen. They are then asked, "With the green pen, please go back and label, if any, biologically inspired elements," and had 5 minutes to do so. This ensured that any BID elements identified before they were explicitly told were written in black pen, and anything added after was clearly seen in green. This distinction is important as it allows differentiation between the initial design elements and those influenced by the BID prompt, providing a clearer understanding of the participants' natural inclination towards BID versus their response to the explicit instruction. An example of one response can be seen in Figure 2.

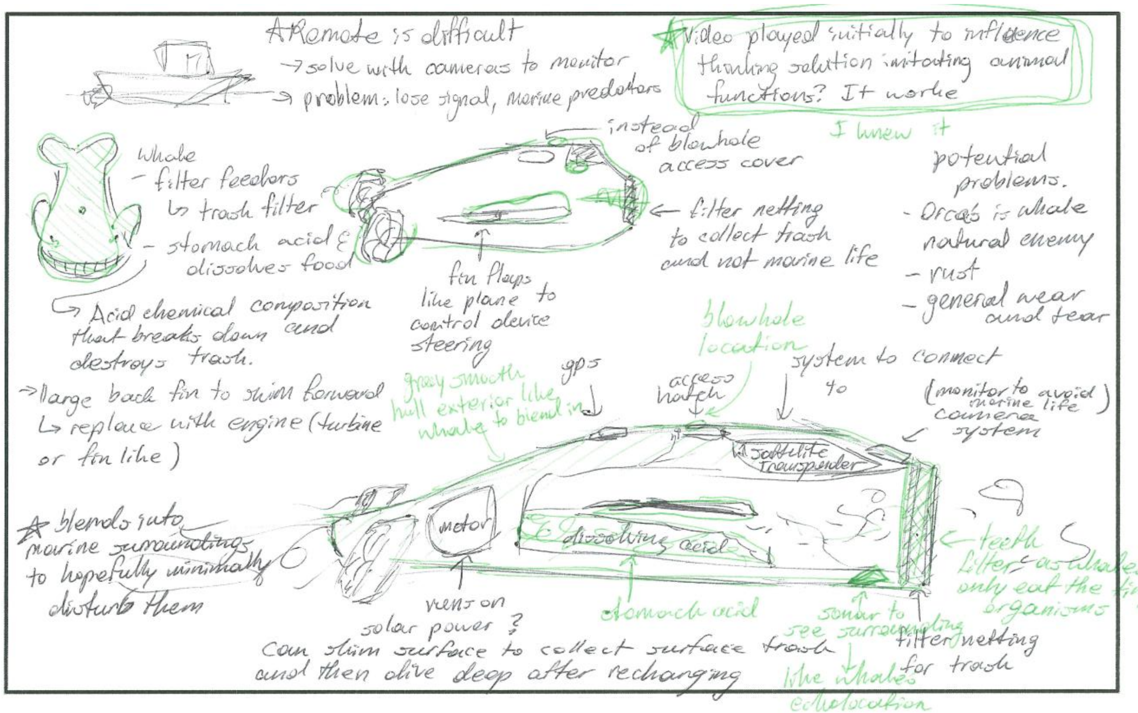


Figure 2: Example Participant Solution Including Black and Green Pen Ink

The procedure concludes with a post-evaluation survey (10 minutes), which was administered after the design challenge to assess changes in participants' understanding of biologically inspired design. The post-evaluation survey consists of multiple-choice and fill-in-the-blank questions and can be seen in Appendix B.

2.3 Evaluation Criteria

Designs in this study were evaluated to determine their compliance with the specified requirements, including the presence and effectiveness of biologically inspired elements in solving the design challenge and overall functionality. An evaluation was conducted using a rubric to assess whether the generated designs met the user requirements (Appendix C). Participants were not shown the rubric and were not informed of the specific evaluation criteria during the activity to ensure unbiased, authentic design responses. The rubric was developed by the authors with an iterative process to ensure that the raters agreed that the criteria was relevant and included in the script. The rubric scores each design across 14 requirements and the inclusion of BID, with scores ranging from 0 to 2: 0 indicates the participant did not meet the requirement, 2 indicates the participant demonstrated the requirement comprehensively, and 1 indicates that the participant somewhat met the requirement, either by accident or with an incomplete explanation. Each requirement includes a detailed description of the scores for the raters' reference.

To ensure the assessment process is consistent and objective, multiple evaluators independently reviewed each design based on the same criteria, establishing inter-rater reliability (IRR). Recent research emphasizes the importance of granular reliability analysis in rubric development, as overall agreement metrics can sometimes mask significant variations in how raters interpret specific criteria [25]. This approach ensures a thorough examination of each design's adherence to the requirements, the innovative use of biologically inspired principles in addressing the design challenge. Furthermore, the iterative nature of rubric development, which involves repeated evaluations and refinements, is essential for achieving IRR [26]. The analysis was conducted by a team consisting of a PhD professor and a master's-level student to ensure IRR. The raters first scored a set of 3 designs, followed by a set of 5 designs, comparing their evaluations with those of other rater to calibrate their scoring before proceeding with the rest of the designs. Cohen's kappa coefficient, percent agreement, and Pearson's correlation coefficient were to ensure greater than 80% agreement between raters, which reflects excellent agreement [27]. The average score of the two raters were used for all total rubric score analysis.

Once IRR is achieved, an independent sample *t-test* was conducted to compare the performance of participants in Condition 1 versus those in Condition 2, based on their rubric scores. Additionally, the study assessed learning outcomes by comparing post-assessment survey results for each participant, along with a comparative analysis of these outcomes between the two participant groups.

2.4 Ethical Considerations

All participants were briefed on the study's purpose and provided with informed consent forms. Participants were also assigned a random 5-digit participant ID number to keep their personal data confidential. The study was reviewed and approved by the university's Institutional Review Board (IRB), ensuring that it met ethical standards for research involving human subjects, approval number 25-057.

3 RESULTS

3.1 Inter-rater Reliability

Out of the 26 participants, 27 design solutions were submitted, with one participant submitting two design solutions. Of the 27 solutions, 9 were from the control group and 18 were from the BID intervention group (including the participant who submitted two solutions).

The inter-rater reliability (IRR) analysis had excellent agreement between raters. Cohen's Kappa of 0.863 indicates strong agreement after adjusting for chance, above the threshold of 0.80, which is considered excellent [27]. The Percent Agreement calculation showed that raters agreed on 86.37% of the evaluations, providing a straightforward measure of agreement. Furthermore, the Pearson correlation coefficient of 0.867 indicates a strong positive linear relationship between the raters' evaluations. Together, these values indicate a reliable assessment process.

3.2 Statistical Analysis

The average total rubric score was higher for the unprimed group (mean=20.8, n=9) than for the BID primed group (mean=17.1, n=18). The BID Primed group showed greater variance (ranging from 8-29) while the unprimed condition ranged from 14-27. When comparing the rubric scores for two tested conditions: BID Primed and Unprimed, the data is displayed as a percentage of each condition to facilitate easier visual comparison. It is important to note that Condition 1: BID Primed had 18 responses, while Condition 2: Unprimed had 9 responses. Descriptive statistics for the BID Primed condition include a mean of 17.14, median of 17.25, mode of 16, and range of 21. For the Unprimed condition, the mean of 20.78, median of 20.0, mode of 20, and range of 13 (Figure 3).

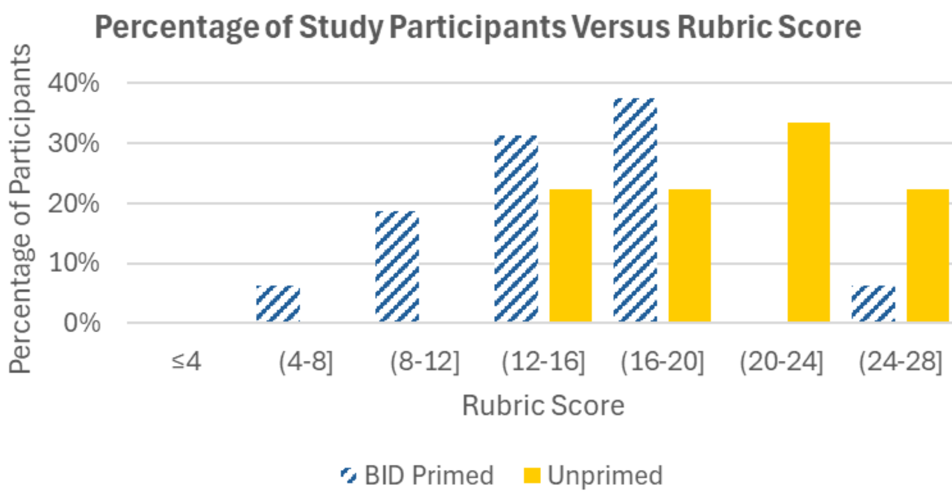


Figure 3: Histogram of Rubric Scores for Two Tested Conditions
Data displayed compared to 100% of each condition to allow easier visual comparison. The reader is cautioned to remember, however, that Condition 1: BID Primed had 18 responses, while Condition 2: Unprimed had 9 responses.

Prior to conducting additional statistical tests, the normality of the groups was checked with the Shapiro-Wilk test, and z-scores were checked to address any potential outliers. Levene's Test for Equality of Variances was also conducted to assume equal variance. Independent sample *t*-tests yielded two interesting findings. First, the results indicated that the biologically inspired design priming video did not influence the participants' design solutions compared to the control video (M = -3.667, SD = 2.173), demonstrating no statistically significant difference between the conditions, t(25) = -1.687, p = 0.104. These results did not change when considering factors from the pre- and post-surveys including participant confidence, previous BID experience, and demographics. Secondly, a *t*-test comparing BID scores on the rubric based on whether participants had biologically inspired elements in their design solutions before or after being told to label BID elements with green pens showed a statistically significant difference in BID scores between groups with different labeling timings (M = 0.81, SD = 0.24), t(19) = 3.349, p = 0.003. Additional *t*-tests were performed to examine additional explanatory factors for rubric performance including script annotations and the presence of BID elements were not significant. This analysis revealed that while the priming video, script annotation, and presence of BID elements did not significantly influence scores, the timing of labeling BID elements did impact the evaluation of BID elements.

Finally, several regressions analyses were performed to determine any predictive factors for rubric performance or BID quality (Table I). These regressions considered all solutions from both groups. Of the nine regressions performed, two were significant. First, a key finding was a significant negative correlation between the presence of BID before labeling was explicitly asked and after labeling ($r = -0.609$, $p = 0.003$). This suggests that students who labeled BID elements of the task earlier produced higher-quality solutions, indicating that early focus on biologically inspired strategies helps align solutions with requirements. The second statistically significant correlation was a strong negative correlation between the presence of BID concepts in solutions and BID rubric scores ($r = -0.892$, $p < 0.001$). The BID concept for each design involved determining whether each design incorporated biologically inspired elements. The BID rubric addressed the functionality of those biologically inspired elements. This contradicts the hypothesis, as the presence of BID concepts in solutions was negative, they were explicitly asked to label any BID elements compared to after they were explicitly asked correlated with higher rubric scores. This could indicate misalignment between BID principles and the rubric's focus, or challenges in effectively integrating BID into solutions.

Table I: Summary of Correlation Analysis.
Significance is defined as p<.05, annotated with italics.

Comparison	**Pearson Correlation (r)**	**p-value**	**Interpretation**
BID elements in participants' solutions before and after they were explicitly asked to label any BID elements, based on their isolated BID scores from the rubric.	-0.609	*0.003*	Participants had higher BID scores on their rubric if they had BID elements present before they were asked to go back and label the BID elements compared to after being asked.
The presence of BID elements before and after participants were explicitly asked to label any BID elements.	0.34	0.131	Whether participants had BID elements or not was not dependent on when they labeled their BID elements whether it was before or after they were explicitly told.
The presence of BID elements before and after participants were explicitly asked to label any BID elements (based on the presence of annotations in their copy of the script).	0.355	0.114	Annotations did not significantly affect the presence of BID elements.
Overall scores and BID scores based on the rubric.	0.225	0.259	Overall scores do not significantly relate to the BID scores.
Overall scores and the presence of BID elements.	-0.303	0.125	The presence of BID elements does not significantly impact the overall scores.
Overall scores and the presence of annotations.	0.131	0.515	Annotations do not significantly affect the overall scores.
BID scores based on the rubric and the presence of BID elements.	-0.892	*< 0.001*	As the BID scores increase, the presence of BID elements tends to decrease.

BID scores based on the rubric and the presence of annotations.	0.019	0.924	Annotations do not significantly impact the BID scores.
The presence of BID elements and the presence of annotations.	-0.236	0.236	The presence of BID elements does not significantly relate to the presence of annotations in the script.

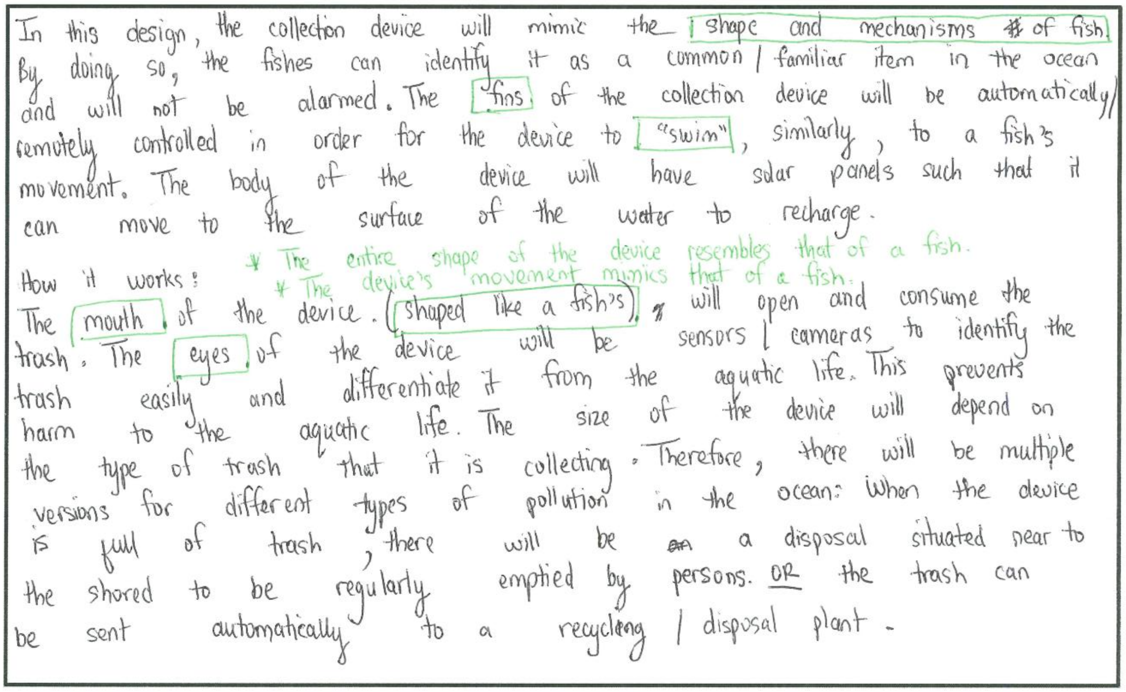
Finally, and surprisingly, annotation of the script did not show significant correlations with other variables ($p = .515$). This suggests that while annotation of the problem statement script might seem like a logical factor in solution quality, it did not correlate with performance in this sample.

4 DISCUSSION

This study sought to evaluate the hypothesis: *if undergraduate engineering students are primed with information about biologically inspired design, they will outperform students who were not primed in a design challenge (as measured by requirement fulfillment) because the BID priming will enhance solution quality.* The results fail to reject the null hypothesis, the findings did not reveal a statistically significant improvement in overall solution quality between participants with BID priming and those in the control group. However, notable patterns and areas for further exploration emerged.

The first significant observation was the relationship between the timing of BID labeling and solution quality. Participants who identified BID elements earlier in the design process (written in black versus green) tended to generate solutions more aligned with design requirements ($M = 0.81$, $SD = 0.24$), $t(19) = 3.349$, $p = 0.003$. This suggests that early use of BID concepts may enhance a designer's ability to apply these principles effectively. Nevertheless, we did not find evidence that the mere presence of BID improves design outcomes. The inclusion of BID concepts in a solution was negatively correlated with BID rubric scores, highlighting potential misalignments between creative, biologically inspired designs and our assessment frameworks. The R^2 value for this correlation was 0.371, indicating that about 37.1% of the variance in BID scores can be explained by the timing of labeling (Table I). Additionally, the slope of -0.609 suggests a negative relationship, meaning that as the presence of BID elements increases, the BID scores of the rubric tend to decrease, and vice versa.

Another interesting finding was that two of the top-scoring participants in the study produced solutions that consisted solely of written descriptions, with no accompanying drawings (Figure 4). This suggests that written explanations of functionality and design can be just as effective as visual representations in meeting design requirements.



In this design, the collection device will mimic the shape and mechanisms of fish. By doing so, the fishes can identify it as a common / familiar item in the ocean and will not be alarmed. The fins of the collection device will be automatically / remotely controlled in order for the device to "swim", similarly, to a fish's movement. The body of the device will have solar panels such that it can move to the surface of the water to recharge.

How it works: * The entire shape of the device resembles that of a fish. * The device's movement mimics that of a fish.

The mouth of the device (shaped like a fish's) * will open and consume the trash. The eyes of the device will be sensors / cameras to identify the trash easily and differentiate it from the aquatic life. This prevents harm to the aquatic life. The size of the device will depend on the type of trash that it is collecting. Therefore, there will be multiple versions for different types of pollution in the ocean. When the device is full of trash, there will be a disposal situated near to the shored to be regularly emptied by persons. OR the trash can be sent automatically to a recycling / disposal plant.

Figure 4: An Example of a Participant that did not Submit a Sketch.

One of these two participants was also the only student to submit two solutions. Interestingly, the participants scored 25/32 on the solution where they used BID principles and only 12/32 on the solution where they did not incorporate BID. This highlights the potential impact of BID on solution quality when effectively integrated, while also raising questions about the role of visual representations versus written descriptions in design communication and assessment.

Additionally, participants' understanding of BID was closely tied to their performance. Among those who scored a 2 (fully meeting the rubric criteria for BID elements), 12 out of 13 provided what could be considered a "good definition" of BID during the post-assessment. A good definition of biologically inspired design (BID) involves drawing inspiration from natural principles and biological systems to solve engineering challenges. These definitions include references to nature as a source of inspiration and addresses how biological strategies can be adapted to meet human design needs [20]. In contrast, only 1 of the 6 participants who scored a 1 (partially meeting the rubric criteria) provided a good definition, and only 1 of the 8 participants who scored a 0 (failing to meet the rubric criteria) did so. This indicates that a deeper conceptual understanding of BID is closely linked to the ability to effectively incorporate it into design solutions, highlighting the importance of instruction and clear conceptual grounding when introducing BID principles.

Furthermore, the decision to base the scoring rubric on requirement fulfillment may have unintentionally favored conventional approaches over innovative, biologically inspired ones. There may be an mismatch between creativity and requirement fulfillment that requires further investigation. This misalignment could account for the lower scores associated with BID-present solutions, as creative elements might not have been fully recognized or valued by the rubric criteria. Another consideration is the contextual influence of the participants' academic background. All participants were enrolled in a Graphical Communications course, which emphasizes technical drawing and engineering principles. This prior knowledge might have inadvertently influenced the design approaches of both groups, diluting the effect of the BID intervention.

Despite these challenges, the study highlights the potential of BID as a pedagogical tool. BID encourages students to explore unconventional solutions, fostering creativity and innovation, which aligns with the broader goals of engineering education to prepare students for complex, real-world challenges. The positive correlation between early BID labeling and solution quality suggests that introducing BID principles early in the design process, and integrating them throughout, can improve outcomes. Additionally, the observed relationship between BID understanding and design quality highlights the value of reinforcing conceptual foundations in BID education. However, these findings also emphasize the need to evaluate the role of creativity or BID in requirement fulfillment (the basis of our rubric).

4.1 Limitations

This study has several limitations that warrant further investigation. Future research should explore more comprehensive instructional methods, such as workshops, scaffolding exercises, or iterative feedback sessions, to deepen students' understanding of BID. Recruiting a larger, more diverse sample will improve the reliability and generalizability of findings. Future studies could also evaluate solutions twice, once before and once after BID elements are labeled, to determine whether incorporating BID improves performance. Finally, exploring the long-term effects of BID training on students' ability to apply these principles in professional contexts could provide valuable insights.

The lack of significant differences between the experimental and control groups could stem from various factors. One notable limitation was the small and uneven sample sizes, which may have influenced the results. The control group consisted of only nine participants, and six of them scored above a 20/32 on their solution, resulting in unexpectedly high average scores for the group. This was surprising given that the history of sketching video used in the control condition did not include any information relevant to improving design solutions. In theory, if the BID priming had no effect, both groups should have scored similarly. The higher control group scores could be attributed to the small sample size and the greater variability that accompanies it. Additionally, the limited number of participants was further exacerbated by technical difficulties during one round of data collection and reluctance among some students to participate in the study.

Instructional barriers may also have contributed to the findings. Specifically, participants were not taught systematic methods for applying BID, such as functional decomposition or analogy mapping. The brief intervention video shown to participants in Condition 1 (the biologically inspired design priming condition) served as a general introduction rather than a structured instructional guide. As a result, students may not have received adequate support or the tools necessary to effectively apply BID principles in their designs. This limitation reflects the study's intentionally foundational design and highlights the need for more comprehensive BID instruction in future research. Although the video provided introductory knowledge, it likely lacked the depth required to help students translate abstract BID concepts into actionable design strategies. Future work will explore more detailed and structured instructional approaches to support effective BID integration.

5 CONCLUSION

We examined our central question on if biologically inspired design priming would improve undergraduate student design outcomes by conducting a comparative analysis of two conditions: one exposing participant to BID priming and the other receiving a control intervention. The findings did not validate our hypothesis that BID enhances the quality student-generated solutions but do provide two contributions.

First, this study highlights the relationship between the timing of BID application and solution quality. Participants who identified BID elements earlier in the design process produced solutions better aligned with the design requirements, suggesting the importance of early conceptual grounding in BID education.

The second contribution is the need for refinement in instructional methods and evaluation frameworks. While BID principles help enhance creativity and innovation, their effective integration into engineering curricula faces challenges such as misalignment with traditional assessment metrics (requirement fulfillment).

Although providing insight into the pedagogical application of BID and the contextual factors influencing its effectiveness, there are still outstanding questions. Future work can focus on addressing instructional and assessment limitations, scaling the study with larger, more diverse samples, and investigating the long-term impacts of BID training on professional engineering practices. Additionally, the development of tailored rubrics and enhanced instructional strategies is worth investigating. Educators and curriculum designers should consider introducing BID concepts earlier in the design process and pairing instruction with scaffolding or guided examples to support novice learners. Because early identification of BID elements was associated with stronger performance, instructors may benefit from emphasizing BID during the initial stages of design activities. Finally, investigating the long-term impacts of BID training on professional engineering practices can provide a deeper understanding of BID's role in shaping creative, sustainable engineering solutions.

Future studies can also examine incorporating functional decomposition methods that have proven successful in biologically inspired design. Hernandez and Watson (2024) demonstrated that biologically inspired functional decomposition, like deriving decentralized network operations or amplification mechanisms from insect behavior, can create frameworks for resilient system design. Integrating these methods into instructional materials could provide participants with concrete, structured approaches to applying BID principles, potentially reducing the disconnect between the abstract understanding of biologically inspired design (BID) principles and the participants' ability to apply those principles effectively to their design tasks observed in this study. Booth et al. (2024) further examined the challenges novice engineers face when applying functional decomposition, including high cognitive load and difficulty distinguishing parts from functions. Their findings highlight the importance of tailored instructional methods, such as detailed examples of function trees or guided steps for energy-flow and top-down methods, to support deeper learning and effective application of BID concepts.

By continuing this research, we provide insight into BID's role in fostering a new generation of engineers prepared to tackle real-world challenges. Thus, this article provides a key first step towards supporting more innovative engineering solutions, desperately needed due to the growing complexity of global challenges.

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APPENDIX A: Study Script with Embedded Requirements

ID Number: _______________

Sam Reefmender: "Hey, I'm thrilled we're meeting today. I've got this really cool idea that's been brewing in my mind. You know, ever since I was a child, I've been fascinated by the ocean—the way it seems endless, full of mystery and life. It's heartbreaking to see how much trash ends up in our beautiful seas. That's why I've been dreaming up an underwater trash collection system. Something efficient, environmentally friendly, can move itself, and capable of making a real difference."

Nicholas Tinker: "It's inspiring to hear someone speak so passionately about protecting our oceans. I'm intrigued by your idea and confident we can turn it into something practical and impactful. What are you envisioning?"

Sam Reefmender:" Um... well, the main goal is to collect different types of trash, like microplastics and larger debris, without harming the ocean floor. We do not want any safety issues, so it would be amazing if it could be remotely controlled and monitored and powered, since the ocean is so deep and dark."

Nicholas Tinker: "I see your vision, and it's clear you've put a lot of thought into this, but it is definitely within our reach. The depth and complexity of the ocean environment requires a thoughtful approach."

Sam Reefmender: "Exactly! And, you know, it's not just about the trash. It's about reconnecting with the ocean. I remember this one time; I went scuba diving near a coral reef. The colors, the tranquility, the life, it was like another world. A world we need to protect. That experience made me realize the importance of a project like this one. It goes beyond just cleaning up. It's about preserving that beauty for future generations."

Nicholas Tinker: "That's a powerful story. It really puts into perspective why we're doing this."

Sam Reefmender: "It is, isn't it? That's where I think this solution could help. Overall, it should be efficient, reliable, and straightforward to operate. We're tackling ocean trash head-on, ensuring our solution makes a significant impact today. It's also important that whatever we design doesn't just move the problem elsewhere but actually deals with the collected trash."

Nicholas Tinker: Got it! I'm really excited about bringing your vision to life. Let's get started on this as soon as we can. I'll make sure whatever we come up with is not only effective but also easy for anyone to use! I can even imagine this being deployed in different oceans as long as we consider local laws. How does that sound?

Sam Reefmender: That sounds fantastic! I'm really excited about the potential here and appreciate your dedication to making this idea a reality.

__**Your task:**__ Create a design solution to the problem above. Use a black pen to create your design, identify, and label details to the solution. Please feel free to write descriptions of the functionality of each aspect of the design as well.

Please use a clean sheet of paper for each design and write your participant ID number at the top.

APPENDIX B: Post-Evaluation Survey

ID Number: _______________

Post-Assessment Survey

Section 1:

This assesses your current knowledge and confidence in bioinspired design and engineering decision-making.

Instructions

Please complete the following questions to the best of your ability. Be sure to circle your answer.

1. Select the statement that best describes your knowledge on bio-inspired design **BEFORE** participating in the study:

    I've never heard of it

    I've heard of it but don't know the definition

    I've heard of it, and I understand what it is

    I've heard of it and have done research in the area

    I've heard of it, and I've had previous coursework on it

2. Select the statement that best describes your knowledge on bio-inspired design **AFTER** participating in the study:

    I've never heard of it

    I've heard of it but don't know the definition

    I've heard of it, and I understand what it is

    I've heard of it and have done research in the area

    I've heard of it, and I've had previous coursework on it

Section 2: Short Answer

1. What is bio-inspired design?

2. What were the requirements of the design challenge? (Use Bullet Points)

ID Number: _______________

Section 3: Confidence Assessment

On a scale of "Strongly Agree" to "Strongly Disagree," rate your agreement with the following statements:

Instructions

Please circle the option that best applies to you for each statement:

1. I understood the requirements of this design challenge.
   Strongly Agree Agree Neutral Disagree Strongly Disagree

2. I can identify effective bio-inspired design solutions.
   Strongly Agree Agree Neutral Disagree Strongly Disagree

3. I am confident that I can create bio-inspired design solutions.
   Strongly Agree Agree Neutral Disagree Strongly Disagree

4. I believe I can make sound engineering decisions in bio-inspired design.
   Strongly Agree Agree Neutral Disagree Strongly Disagree

5. I believe I can use bio-inspired design as a tool to improve my engineering designs.
   Strongly Agree Agree Neutral Disagree Strongly Disagree

APPENDIX B: Evaluation Rubric

Criteria	Points	Description of Ranges	Score
Trash Collection	0-2	0: Design does not collect trash. 1: Design collects some types of trash accidentally or with low frequency. 2: Design collects trash efficiently and comprehensively.	
Trash Collection Efficiency	0-2	0: Design has minimal functionality related to trash collection. 1: Design addresses trash collection but lacks efficiency. 2: Design effectively addresses trash collection with high efficiency.	
Versatility in Trash Collection	0-2	0: Design cannot handle different types of trash. 1: Design can handle some but not all types of trash effectively. 2: Design is versatile, effectively handling a wide range of trash types, including small and large debris.	
Trash Handling	0-2	0: Design does not effectively handle, or process collected trash. 1: Design partially handles or processes trash but may not fully address the problem. 2: Design fully processes or destroys collected trash.	
Remote Operability	0-2	0: Design lacks remote control. 1: Design includes some level of remote control, or has elements to enable remote control (but remote control not explicitly specified) 2: Design offers comprehensive remote-control capabilities.	
Remotely Monitored Craft Behavior	0-2	0: Design lacks monitoring capabilities. 1: Design includes some level of monitoring. 2: Design offers monitoring capabilities.	
Environmental Friendliness	0-2	0: Design poses risks to the ocean environment or lacks environmental sustainability. 1: Design minimizes harm and promotes sustainability. 2: Design is environmentally friendly, promoting sustainability without harming the ocean and is intentionally designed elements to reduce risk of ocean environment.	
User Safety	0-2	0: Design poses safety risks. 1: Design is generally safe with some potential risks. 2: Design is completely safe, posing no risks.	
Autonomy	0-2	0: Design requires constant human intervention or not specified.	

		1: Design shows some level of autonomy or has elements to enable autonomy. 2: Design is fully autonomous.	
Power Adequacy	0-2	0: Design has inadequate power or no power supply. 1: At least a portion of the design is adequately powered but may have limitations. 2: Entire design is adequately powered for deep and prolonged operations.	
Adaptability	0-2	0: Design is not adaptable for different oceanic conditions. 1: Design is somewhat adaptable. 2: Design is highly adaptable (ex. deep waters and/or high current).	
Operational Efficiency	0-2	0: Design is inefficient in operations. 1: Design is somewhat efficient. 2: Design is highly efficient, maximizing trash collection and handling.	
Reliability	0-2	0: Design frequently fails/has downtime or contains elements that would frequently fail/have downtime. 1: Design is generally reliable with occasional issues, or reliability not addressed. 2: Design is highly reliable, with minimal downtime.	
User-Friendliness	0-2	0: Design is difficult for users to operate or interface not shown. 1: Design is somewhat user-friendly but may require some technical knowledge. 2: Design is easy to operate, requiring no extensive technical knowledge.	
Impactfulness on Ocean Preservation	0-2	0: Design has no significant impact on ocean preservation. 1: Design makes some impact but may not fully address the scope of ocean preservation. 2: Design makes a significant, positive impact on ocean preservation and cleanliness. (ex. >$20m^3$ trash removal)	
BID	0-2	0: BID elements are present and labeled 1: BID elements are present but not labeled/ do not have function 2: BID elements are present and labeled/ have function	
		Total:	

APPENDIX C: Summary of Biologically Inspired Design Video Presentation

Biologically Inspired Design Video

Slide 1: What is Biologically Inspired Design?
Biologically Inspired Design (BID) is a problem-solving approach that uses analogies from nature to inform and improve human technology. The process involves identifying functional strategies used by organisms and adapting them to engineering challenges.

Slide 2: Example – Shinkansen Bullet Train (Problem Introduction)
Japan's Shinkansen bullet train initially created loud "tunnel booms" when exiting tunnels due to pressure waves generated at high speeds. This noise pollution disturbed residents and posed a design challenge for engineers.

Slide 3: Example – Shinkansen Bullet Train (Nature-Inspired Innovation)
Engineers redesigned the train's front based on the kingfisher bird's beak, which allows it to dive into water with minimal splash. This change eliminated tunnel booms, increased speed by 10%, and reduced electricity use by 15%.

Slide 4: BID is Used Across Many Biomes
BID applications draw from a wide variety of organisms and ecosystems. Solutions can originate from land, aquatic, aerial, or even extreme environments, showcasing the vast scope of biological inspiration in design.

Slide 5: Other Notable Examples of BID
In addition to the bullet train, well-known BID examples include gecko-inspired adhesives, lotus leaf-inspired self-cleaning surfaces, and shark skin-inspired antibacterial surfaces, among others. These innovations demonstrate the versatility of natural strategies in addressing engineering problems.

Slide 6: BID Design Approaches
There are two standard approaches to BID:

> Problem-driven – Begins with a specific technical problem, and researchers seek out relevant biological analogs.
>
> Solution-driven – Starts by identifying an interesting biological function or structure, which is then applied to a human challenge.
> These approaches offer flexible pathways for innovation and are well-established in BID research.

APPENDIX D: Summary of History of Sketching Video Presentation

History of Sketching Video

Slide 1: What is Engineering Sketching/Drawing?
Engineering sketching is the use of a standardized visual language to clearly convey design concepts and technical intent. It serves as a bridge between conceptual ideas and technical realization, ensuring accuracy and consistency across design documentation.

Slide 2: Purpose of Engineering Sketching/Drawing
Engineering drawings are essential for communication, visualization, documentation, quality control, compliance, cost estimation, and future maintenance or modifications. They are a foundational tool in the engineering design process.

Slide 3: Early Engineering Drawings
Originating in the 14th–15th centuries, early engineering drawings were primarily pictorial and descriptive. Pioneers like Leonardo da Vinci created sketches to explain mechanisms, while Leon Battista Alberti emphasized multi-view drawings for clarity and precision.

Slide 4: Mathematical Influence
The evolution of technical drawings was shaped by the development of descriptive geometry and the Cartesian coordinate system, introduced by René Descartes and Gaspard Monge. These innovations laid the groundwork for multiview and modern CADD practices.

Slide 5: Influence of Interchangeability
During the Industrial Revolution, the demand for standardized, interchangeable parts transformed engineering drawing practices. Originally seen in firearm manufacturing, this shift required highly precise drawings with uniform tolerances and dimensions.

Slide 6: Blueprints
As standardization and mass production grew, so did the need for efficient duplication of design documents. The blueprint process was developed to preserve and distribute engineering drawings across various production sites.

Slide 7: Today's Engineering Drawings
With the rise of computer-aided design and drafting (CADD) in the 1980s–1990s, digital tools revolutionized the creation of technical drawings. Today, CADD is the standard for producing professional, accurate, and modifiable design documentation.