Searching for Deep Understanding: Implementing a Mechanical Engineering Design Process in K9-K12 Physics Classrooms to Identify and Improve Levels of Physics Intuition and Content

By

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Abstract

This experiment tested the level of Physics content knowledge of various K9-K12 Physics students in a local Boston high school by having them implement a mechanical engineering design process to solve open-ended design problems. Using MIT's 2.009 and 2.72 Mechanical Engineering project-based classes as models for project planning, a fully hands-on collaborative project was developed whereby students designed, built, tested, and then raced model kit cars driven by compressed gas. Over the course of six weeks, students selected three design elements of their car to change and did detailed analysis to predict how these changes would affect the performance of their car. Major deliverables of the project included a group-kept design notebook that was turned in on a weekly basis as well as a final product brochure that highlighted the major areas of learning that the students experienced with the project. Results of the project were positive. The stock kit car ran anywhere from 20-25mph without modifications, but students achieved speeds of over 95mph by optimizing their design in ways dictated by the laws of physics. Yet, there can be disconnects between what a student produces in his or her work and their true understanding of what they have done. By examining the design notebooks as well as through weekly interactions with the students, it was clear that very few students exhibited true ownership of some very fundamental principles of Physics and mechanics. Yet, these same students tended to do very well in their MCAS (Massachusetts Comprehensive Assessment System) as well as in the framework of traditional classroom testing and assignments. Conclusions can be drawn from this thesis work that although students can demonstrate proficiency of bodies of scientific knowledge in the framework of written tests, their understanding of the material does not go deep enough to immediately apply this content knowledge to solve open-ended engineering problems. The good news is that these students aren't employees of an engineering firm who are expected to arrive with a well founded mastery of their field, instead they are students who are expected to grow and learn from failures. It is clear that hands-on projects like the one developed for this thesis work serve as irreplaceable learning opportunities where students can bridge the gap between textbook learning and the true physical implications of what they learn. Not only this, but they learn basic problem-solving, time, and team management skills that will serve them well regardless of the path they choose after graduation.

Thesis Supervisor: David R. Wallace
Title: Implementing the Mechanical Engineering Design Process in K9-K12 Classrooms

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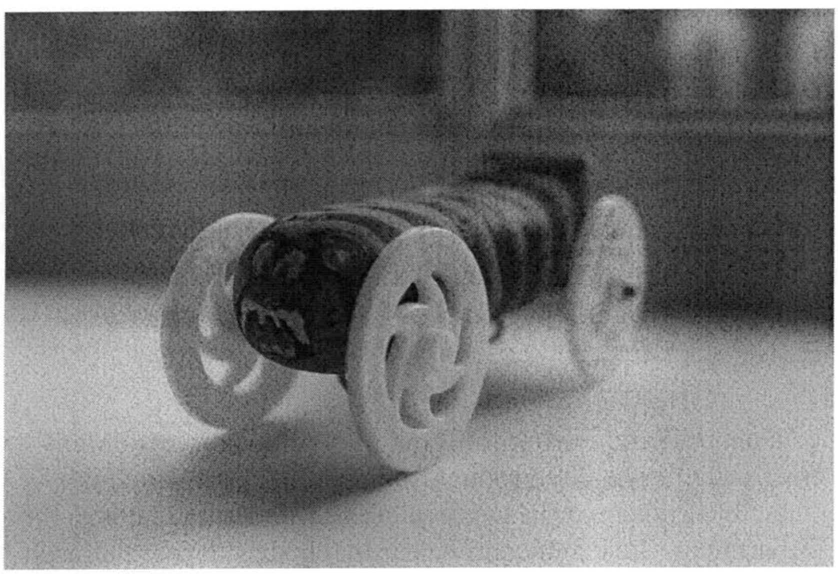

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John Williams

A Very Special Thanks To...

Before anything else, I would like to thank those who provided help in any way with this thesis work.

Charles Duggan

Charles has been a mentor to me in many ways. Not only did he open up his classroom to me for my certification practicum work to become a K12 teacher in Massachusetts, but he also provided invaluable help in the classroom when I couldn't be around. Charles was also the major inspiration for choosing this particular project for my thesis work, his belief and commitment to excellence in teaching as well as his unwavering efforts to implement a hands-on and relevant curriculum to his students is truly inspiring.

Vince Ciarametaro

Vince also opened up his classroom to me for the implementation of this project. His help and partnership proved to be invaluable, as I did not know his students at all until the day the project began. I can tell that Vince appreciates and excels at his work as a teacher, his open-mindedness and pursuit of a dynamic and engaging learning environment will lead him to great places. Thank you so much Vince, it was an absolute pleasure working with you.

Professor David R. Wallace

Professor Wallace provided a tangible framework for the design of this project. Many elements were modeled directly after his 2.009 Product Engineering class, which is perhaps one of the best practical learning experiences available to undergraduates in the Mechanical Engineering Department. It is abundantly clear that he has devoted himself to honing every detail and module of the class to provide a deep and long-lasting impact on his students. As a student of his class, I can affirm that I graduated feeling prepared and confident to enter the world as a productive and functional mechanical engineer. Thank you professor Wallace for all of your guidance and hard work.

(and of course...) The students!

I hope that you learned much and grew from the experience. It would be nice to know you had fun doing it too! In all honesty, I was absolutely blown away by your work ethic, company, and quality of your work. I wish you all the best in whatever it is you choose to do with your bright futures.

Biographical note

John Williams is a candidate for a B.S. in Mechanical Engineering; he hopes to graduate in June of 2010. While studying at MIT, he became involved in the S.T.E.P. teacher education program. Through this program, he discovered his passion for the art of teaching. He is currently awaiting his full Licensure to teach K9-12 Physics in the state of Massachusetts.

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I. Introduction

1. Background

This project has students run through an entire design process (modeled after product testing and design) in order to produce a small scale wooden race car that gets shot down a track with compressed gas. The students work in small groups, learn effective collaborative skills, implement the design processes, race their cars, and finally reflect on how they functioned within the parameters of the project. This project was given in the context of a physics classroom (any level), so a strong emphasis was placed on justifying design decisions using physics principles. If students could take the textbook learning they are used to and apply it to a real system, then they have effectively demonstrated a deep ownership of the curriculum material. It was a hope that applying physics to a real mechanical system would help eliminated common misconceptions and develop students' intuition for the true meanings and relationships that are present within the equations they learn to manipulate in the regular classroom. The effectiveness of this project was judged by how well it revealed students' true level of Physics understanding and also by how well it worked to correct any gaps in their understanding.

Due to pressures to have students test well on standardized exams as well as scheduling pressures on teachers, many students aren't given the time or opportunity to explore true open-ended questions. Instead, they are given worksheets and tests with definitive answers and many students learn to succeed by processes of memorizing and repetition instead of seeking true mastery of the material. We want our students to develop as critical thinkers and dynamic problem solvers, and yet, for the aforementioned reasons, it is extremely difficult to model an environment that exercises these skills in a classroom. This project was designed to give students a sense of what it's like to approach a problem with no known solution. They were encouraged to think creatively and experiment extensively to determine on their own what was the best way to make their car the fastest. This process models the reality of a profession like engineering where solutions are demanded, but there is no solution-manual to refer to for the answer.

2. How it started

Charles Duggan and Vince Ciarametaro have a well-established tradition of implementing quarterly projects that aim to get students to apply this sort of critical thinking. Charles Duggan was nationally recognized for excellence in teaching for his design of a yoyo project, where students work alone or in pairs to design a yoyo that takes as long as possible to descend three flights of stairs. It is an out-of-class project with minimal guidance for the students and students' grades are based only on the finally performance of their yoyo (as well as a short reflection paper) due at the end of the quarter.

The success of this yoyo project allowed Charles to apply for funding for additional projects. He used this funding to purchase a Kelvin Compressed Air Racer Kit that provides a track, sensors, launch system, car blanks, but no curriculum plan for how to use them all in an educational setting. The quarter project was run once with a group of freshman Physical Science students, but no real project objectives were designed besides building a car individually and filling out a sheet of related kinetics problems. It was noted that the cars students produced indeed "looked" good, but very little thought was put into the mechanical optimization side of the design. I saw this as an opportunity to use the new equipment to maximize Physics learning so I asked Charles if I could design a more focused project curriculum that would force students to think more critically about what they were doing with their cars. He agreed and thus this project was born.

3. Influences of project design

Later sections will go into more detail about the project's architecture and objectives, but the overall goal was to design deliverables, supporting materials, and student incentives that would get students to take their textbook knowledge and use it to do real engineering. The specific modules of the project were modeled after two classes that I found to be some of the most practical and learning-rich experiences of my undergraduate career at MIT.

One class, 2.009 Product Design, is a project-based class that emphasizes the use of a structured design process. Students work in large groups of up to 18 people to select a problem they would like to solve with the design of a new product, then they actually take that product all the way up to phase of a functioning prototype. This class is very unique because the process is emphasized as much the product. Students are taught all aspects of product design, including effective group dynamics, business modeling, and the basics of user psychology. An example of a product that came out of this class is shown in figure 1, it is a small-scale manufacturing platform for producing female pads in remote areas from local and readily available materials. A link to the final presentation of this product can be found in the Citations section. The broad theme of this particular year's class was *Emergencies*; every group made a different genre of product so there was no mode of direct competition between products, yet there were modes of competition between overall group performance.

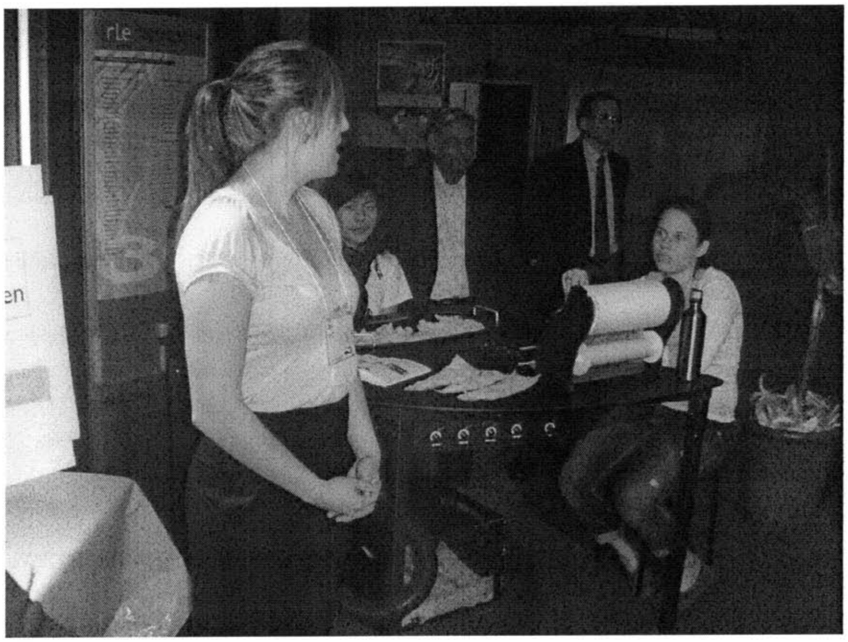


Figure 1: A unique product created by students of 2.009

The second class, 2.72 Elements of Mechanical Design, emphasizes more technical skills involved in designing, modeling, and building highly complex mechanical systems. Students work in groups of 4 to build a precision micro-lathe capable of cutting steel with micron accuracy (seen in figure 2). This class is competition based, so unlike 2.009, all groups design the same machine that gets used in a final competition of machine performance. Another key aspect is that the class is also built to model a professional environment, so best practices of real engineering are taught and students are expected to focus on the processes of their design work as well as just the finished product.

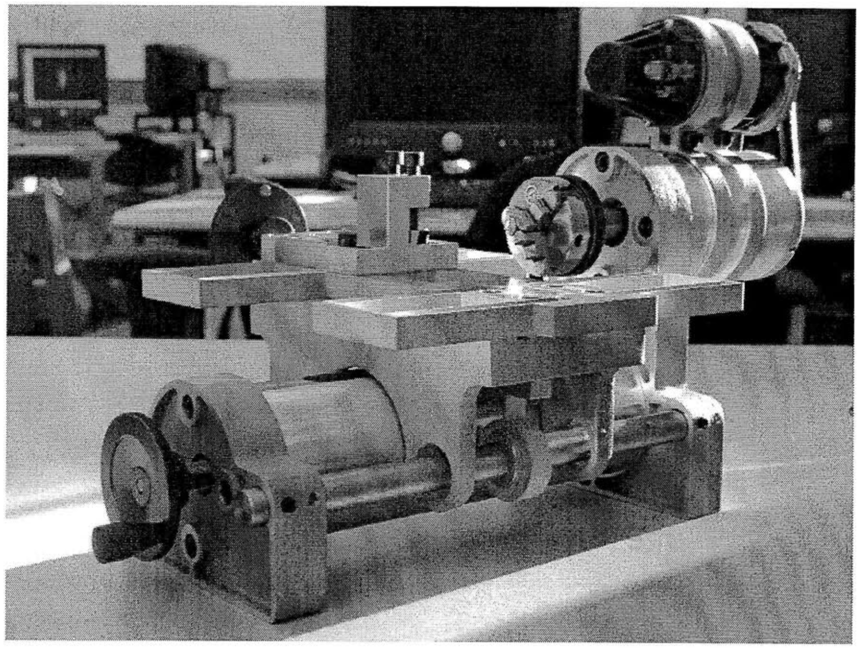


Figure 2: Micro-lathe generated by students of 2.72

Elements from both of these classes were heavily influential in the design of the compressed gas racer project. Specifically, a process oriented grading structure, instruction of best practices, and competition driven student motivation were incorporated.

On a more peripheral note, aside from content learning, one of the biggest learning components students come away with after working on these group projects such as these is the ability to function effectively in a team environment. This learning perhaps has greater value in the context of a life skill since students inevitably encounter team environments regardless of their education/career choices in the future.

II. Foundation and Theory

1. Why push for exploratory hands-on learning experiences in the first place?

The theory for running a project like this is rooted in a constructivist theory of knowledge, which states that students have stronger learning experiences when they can discover knowledge themselves instead of that same knowledge being "told" do them by another person. Daniel S. Domin states in his publication A Review of Laboratory Instruction Styles, that there are four distinct types of lab settings that each has their strengths and weaknesses (Expository, Inquiry, Discovery, and Problem-Based). This lab is modeled after an "Inquiry" instruction style, in which is defined as being inductive and open-ended for students. Students already possess the background knowledge to approach the project/lab, but they are not told exactly how to apply that background knowledge. They must design their own experiments, determine when to apply various principles of learning, and evaluate their own success based on a problem that does not have a well-defined solution. Students are encouraged to take *ownership* of their project, which hopefully leads to improved attitude towards science instruction and increased ability to use formal operational thought. The higher order thought processes that are targeted in this sort of learning include hypothesizing, explaining, criticizing, analyzing, judging evidence, inventing, and evaluating arguments. Traditional Inquiry instruction states that students should be mimicking the role of a junior scientist, but that they are not truly *doing* science, since the instructor already knows the answers. This is where this project differs, however. Students are encouraged to think outside the box as much as possible (while meeting certain design restrictions), as an instructor, I never knew the final answer.

2. Uncovering and targeting student misconceptions by asking them to use Physics content knowledge to solve Engineering problems

Some of the primary areas of physical understanding that were required for mastery of this project included energy conservation, friction, aerodynamics, and inertial effects on dynamic performance. By observing the design decisions of students and also by inquiring as to *why* they made those decisions, common misconceptions in their learning could be unearthed and hopefully corrected.

John Clemens dissects the dynamics of student misconceptions in a paper entitled *Students' Preconceptions in Introductory Mechanics.* This paper aims to interpret the root causes and then identify correct teaching strategies for overcoming these sorts of misconceptions.

The deep qualitative understanding of physics conceptual primitives such as mass, acceleration, momentum, and energy as well as fundamental principles and models such as Newton's laws and conservation laws is what teachers strive to deliver. Yet, according to Clemens, "difficulties at the qualitative level may go undetected, however, because a student's superficial knowledge of formulas and formula manipulation techniques can mask his or her misunderstanding of underlying qualitative concepts." He reasons that some students may manipulate this superficial understanding of equations and mathematics to fit an incorrect preconception they may have. For example, a student who drives to school every day may be aware that they must keep their foot on the gas pedal or else the car will roll to a stop. This student may use that knowledge to wrongfully assume that if an object does not have force acting on it, the force from the engine in this case, that it will not be able to stay in motion. This student is ignoring the role friction plays in slowing the car down.

More importantly, Clemens states that expository methods of teaching such as standing and lecturing don't appear to be good enough. Lab work, debates, and classroom conversations are the best ways to get students to get students to, "articulate and become conscious of their own preconceptions."

This is an immensely important point in the scope of this thesis work because if students don't have a sound understanding of energy conservation, friction, aerodynamics, and inertial effects, they will not be able to select and justify appropriate design decisions on their car. By observing the decisions they make in this context, it becomes clear if their understanding in the relevant realms of Physics content knowledge is shaky or not. By having students run through a design and testing processes, they get a fantastic opportunity to compare their understanding and misconceptions to real results on a mechanical system, hopefully resulting in confirmation and ownership of correct Physics content knowledge.

III. Overview of participating school and classrooms

1. School Profile: Where did it happen?

The school where the project was run is a Title 1 public high school in Massachusetts. Figure 3, Table 1, and Table 2 show some of the key ratings and statistical figures that indicate the level of overall school performance. The information is taken directly from the public Adequate Yearly Progress data provided by the

Massachusetts Department of Elementary and Secondary Education (ESE) for the academic year of 2009. Figure 3 shows the overall performance rating of the school. Figure 4 re-affirms a history of excellent school performance dating back to 2001. Figure 5 shows testing results for the MCAS standardized testing that school performance is based on.

	NCLB Accountability Status	Performance Rating	Improvement Rating
ENGLISH LANGUAGE ARTS	No Status	Very High	On Target
MATHEMATICS	No Status	Very High	On Target

Figure 3: 2009 School performance ratings (Massachusetts Department of Elementary and Secondary Education)

Table 1: History of school performance since 2001 (Massachusetts Department of Elementary and Secondary Education)

		Adequate Yearly Progress History									NCLB Accountability Status
		2001	2002	2003	2004	2005	2006	2007	2008	2009	
ELA	Aggregate	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No Status
	All Subgroups	-	-	Yes	Yes	Yes	Yes	No	Yes	Yes	
MATH	Aggregate	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No Status
	All Subgroups	-	-	Yes	Yes	Yes	Yes	Yes	Yes	No	

Table 2: Student performance for MCAS standardized test (Massachusetts Department of Elementary and Secondary Education)

Grade and Subject	Advanced/ Above Proficient		Proficient		Needs Improvement		Warning/ Failing		Students Included	CPI	SGP	Included In SGP
	SCHOOL	STATE	SCHOOL	STATE	SCHOOL	STATE	SCHOOL	STATE				
GRADE 10 - ENGLISH LANGUAGE ARTS	33	29	52	52	13	15	2	4	159	94.8	39.0	138
GRADE 10 - MATHEMATICS	57	47	23	28	16	18	3	8	159	91.7	45.0	139
GRADE 10 - SCIENCE AND TECHNOLOGY	17	16	54	45	25	29	5	9	151	87.9	N/A	N/A
ALL GRADES - ENGLISH LANGUAGE ARTS	33	16	52	51	13	25	2	8	159	94.8	39.0	138
ALL GRADES - MATHEMATICS	57	23	23	32	16	28	3	16	159	91.7	45.0	139

The following data is also sourced from the ESE . The school has 728 registered students, with about a 50/50 split between boys and girls. The student body is very racially and economically diverse. 20% of students were born outside of the United States and 26% of students have a first language other than English. The average class size is 21 students with a student/teacher ratio of 13:1. 100% of teachers are rated as being "Highly Qualified." Note that the school had 6.25% more students than the state average placing "Above Proficient" on the Grade 10 Science and Technology MCAS test. It also had 22.22% more students than the state average scoring in the "Proficient" category. 13.79% less students were in the "Needs Improvement" category and 44.44% less were in the "Warning/Failing" Category than state average. In 2008, 80% of students took the SAT. The mean Verbal score was 500 and the mean Math score was 525. That same year, 74% of students went on to attend a 4 Year College, 14% went on to attend a 2 Year College and 2% went on to pursue other forms of post-secondary education. These statistics indicate that the school is providing an above-average quality of science education to its students. Physics is one of the represented testing sections students can take on the MCAS in the Science and Technology category.

2. Participating Classes

Four classes participated in the project:

- 2 Grade 9 Honors Physics classes (47 students)
- 1 Grade 12 Honors Physics class (14 students)
- 1 Grade 12 Conceptual Science class (20 students)

At the time of implementing the project, all classes had covered the basics of energy and mechanics. All students had moved on to other units within the frameworks of their respective classes. All classes received the exact same project and guidelines, but the classes did not mix for their rankings and final competition. In total, 81 students representing 18 teams participated.

IV. Resources and Equipment Used

1. Kelvin racetrack equipment

The Kelvin racetrack system consisted of three main components; a compressed air launching system, a speed sensing and display system, and the track itself. Figure 4 shows the system packaging as highlighted in the Kelvin product catalogue.

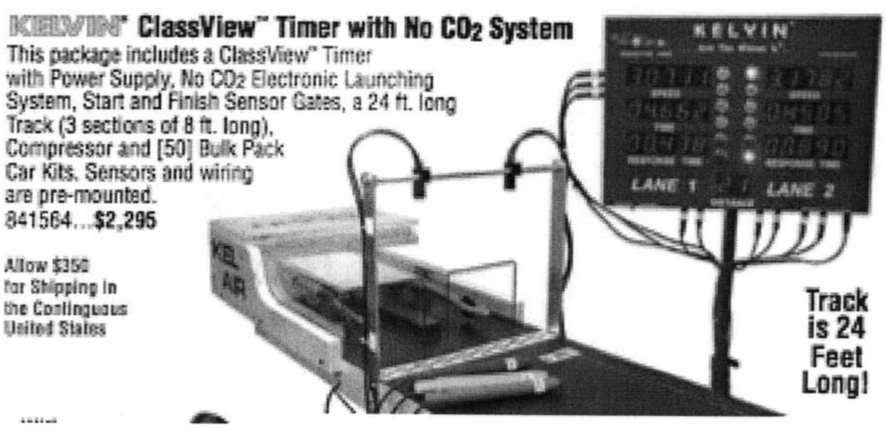


Figure 4: Kelvin racetrack package as purchased for the classroom

The system operates by storing up to 125psi of compressed air for each of the two integrated launching platforms. Cars are snugly fitted onto 3/8in diameter copper tubes that protrude 6 inches from the launching box via matching holes bored into the backs of the cars. The cars are constrained to move along the 24ft long track by a fishing line that is pulled taught down each lane of the track. A system "master" initiates a launch sequence that is visible to students by a Christmas-tree, count-down light that is displayed on a large digital read-out that stands separate from the track. As in regular drag racing, once the christmas tree lights reach the bottom green light, students have up to two seconds to activate electronic actuators that release the compressed air through the brass pipe for 1-2 seconds, thus launching the car. Speeds are measured via two laser pickups located on each end of the track, therefore, only an average speed is calculated. The winner can be determined either by which car reaches the end of the track first (reaction time included) or by which car had the highest average speed. If the lasers do not pick up the car at either end of the track, they automatically lose the race. Figure 5 shows the actual track set up in our classroom. Students were responsible for operating all of the equipment themselves. Figure 8 compares a brass launch tube with a car fitted onto it with a launch tube that has no car fitted. Figure 7 shows a student fitting their car onto the brass launch tube, note that students had full control over how deep and how tightly the car was fitted to the tube. Figure 8 shows a student waiting to launch their car. Finally, Figure 9 shows two cars racing side by side down the track.

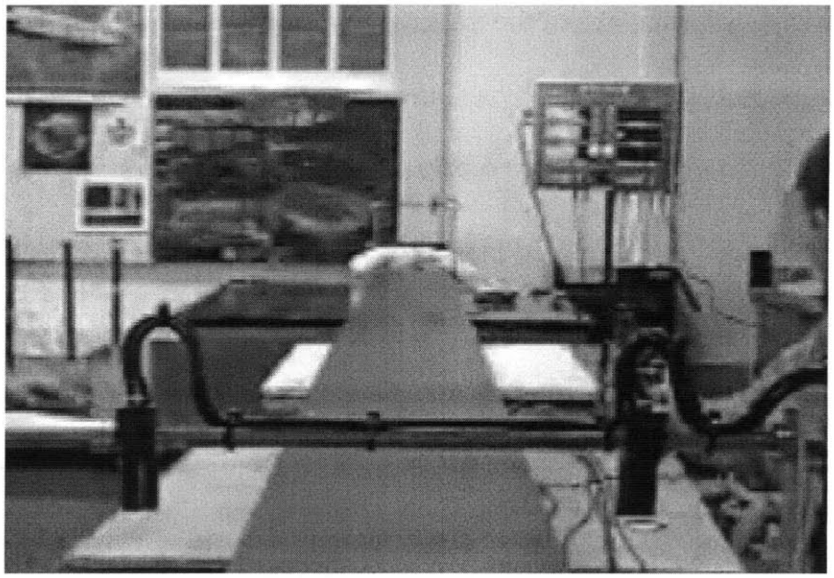


Figure 5: Kelvin racetrack setup in classroom

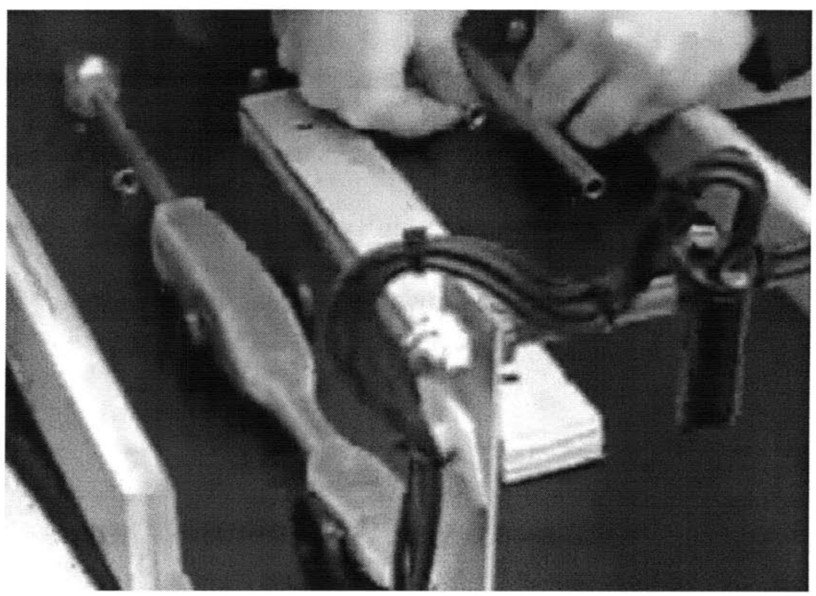


Figure 6: Comparison of launch tube with and without car fitted

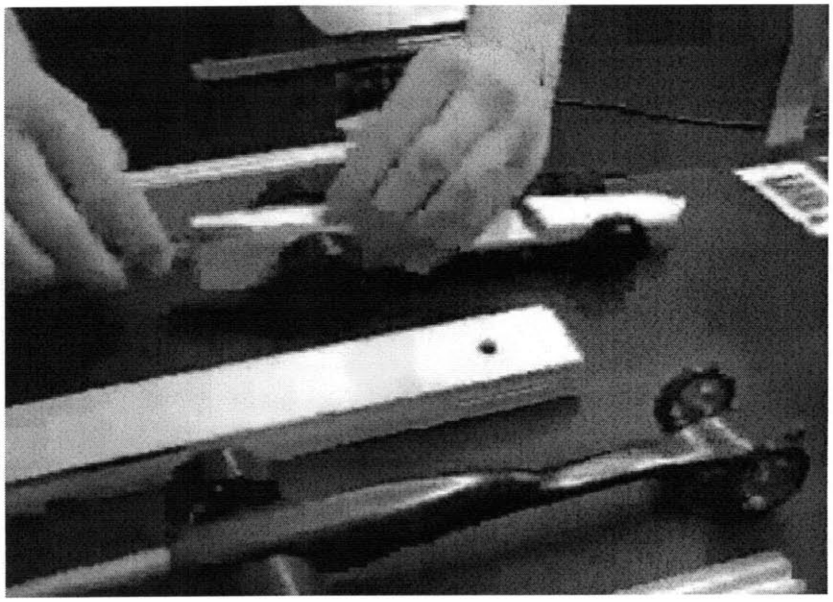


Figure 7: A student readies their car on its launch tube

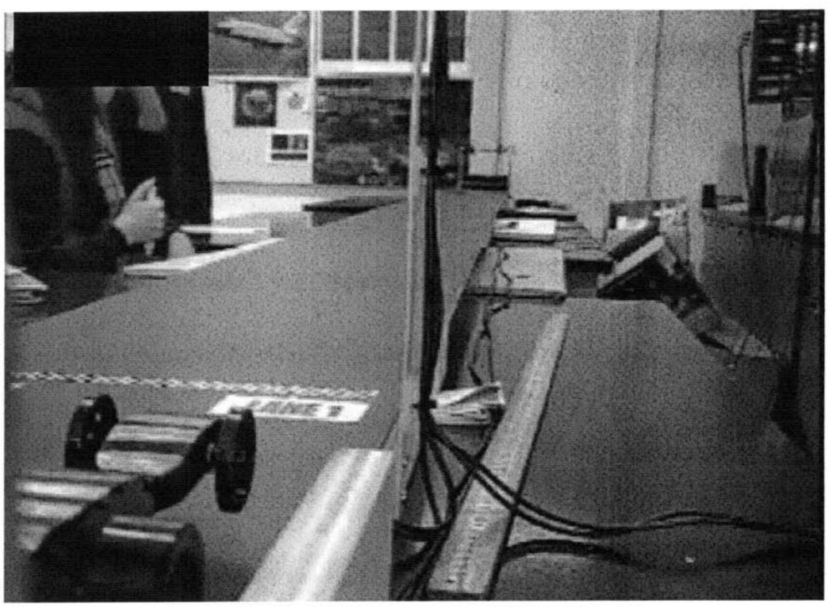


Figure 8: Student (holding controller) waits to launch car

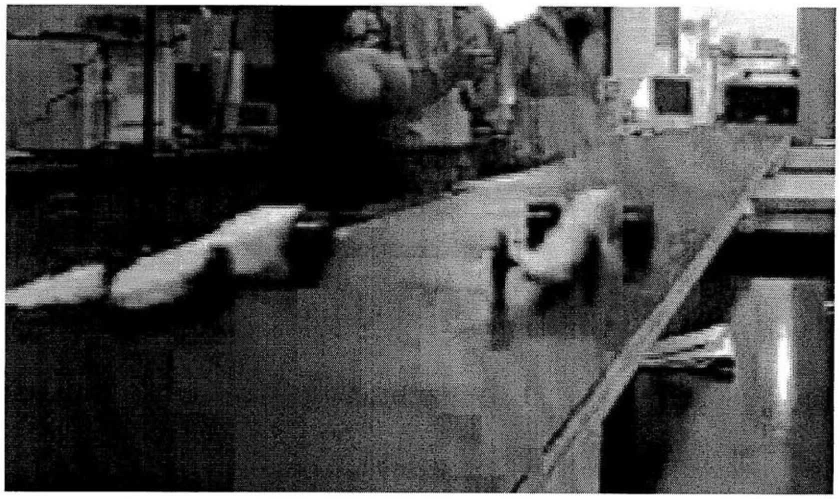


Figure 9: Two cars racing side by side on track

2. Car Kit

The Kelvin racetrack set came with kits to build cars that are compatible with the system. Directions were provided on how to assemble and cut the cars. Two suggested finished car designs from the Kelvin product catalogue are shown on a similar launch system in Figure 10.

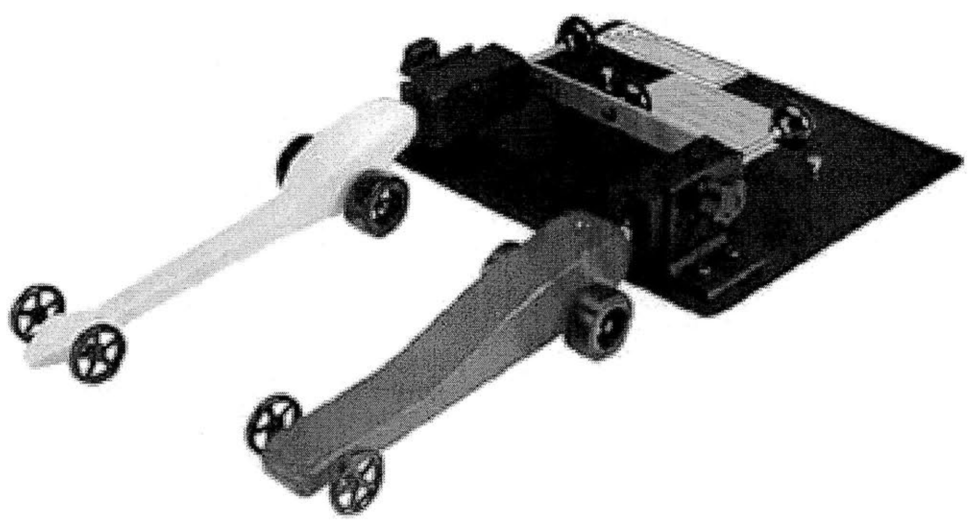


Figure 10: Suggested car designs from Kelvin

Note that the cars shown in Figure 10 are both highly un-optimized designs if the design objective is to make the cars achieve maximum top speeds. These cars are clearly designed with style in mind and not performance. The cars do indeed look like top fuel dragsters (example shown in Figure 9), but the way these model cars function is completely different, so the form they take should intuitively be different as well. In stock form, the car kits could only reach speeds of up to 25mph. Slightly modified kits cars such as the one shown on the left in Figure 12 could reach speeds as high as 30-32mph. Kelvin was called to confirm that these numbers were reasonable and we were told that it was normal to see cars maxing out at 35mph or so.

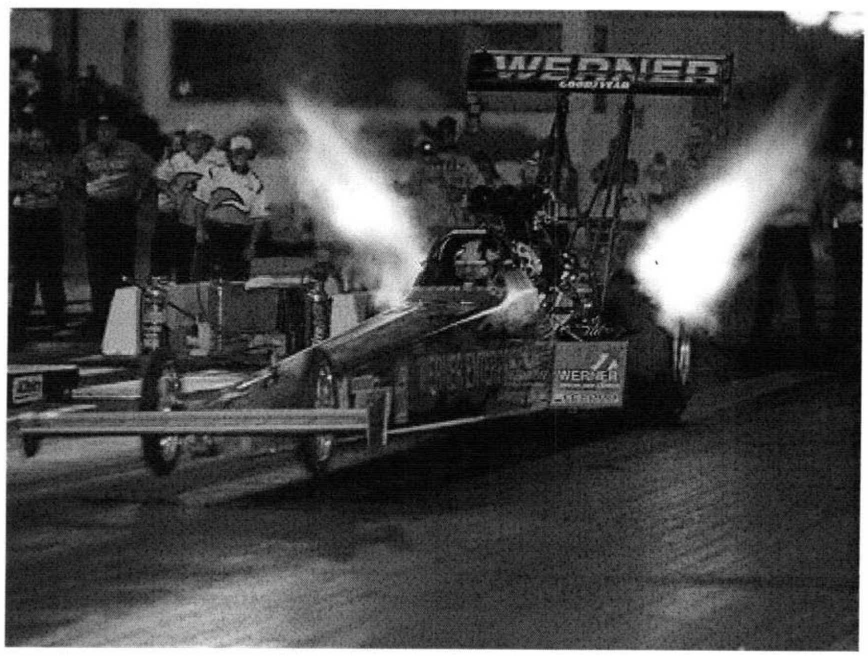


Figure 11: An actual top fuel dragster

Top fuel dragsters must be designed for straight-line stability, whereas the model cars are inherently stable because they are constrained to the fishing line that runs the length of the track. Top fuel dragsters must transmit huge amounts of torque through the rear wheels, so they must have rear tires that have a large contact patch with the ground. The model car delivers no power through any of its wheels; so large tires only add mass and friction. These are just a few examples of how critical thinking about can reveal intelligent design decisions. Since the project was designed to promote this sort of critical thinking, the Kelvin instructions for car design were thrown out the window. Recall that by focusing rigorously on the design object of a high top speed and ignoring all preconceptions about the way a traditional car looks, students were able to take the very same car kits to speeds in excess of 95mph.

Each team received three car kits to do all of their testing and produce a final car from. Unless the students received defective parts, they were not allowed replacement parts under any circumstances. This rule was enforced to encourage students to take care of their parts and also to make them "think before they cut."

Each kit contained the following:

- 1 wood blank with pre-drilled hole to fit launch tube
- 4 small (thin) wheels
- 2 large (wide)wheels
- 2 axles
- 1 straw (suggested use was to use as a bearing for axles)
- 4 washers (suggested use was to place between wheels and body of car)
- 2 eye-hooks (to thread the fishing line through)

Figure 12 shows the kit that each team received three of. Students were not allowed to introduce any new parts to the kit unless it was completely aesthetic or was a lubricant or paint product. There was no restriction on how they used the parts of the kits they were given or if they had to use them at all. The only exception to this rule was the two eyehooks that were a mandatory design component for reasons of safety.

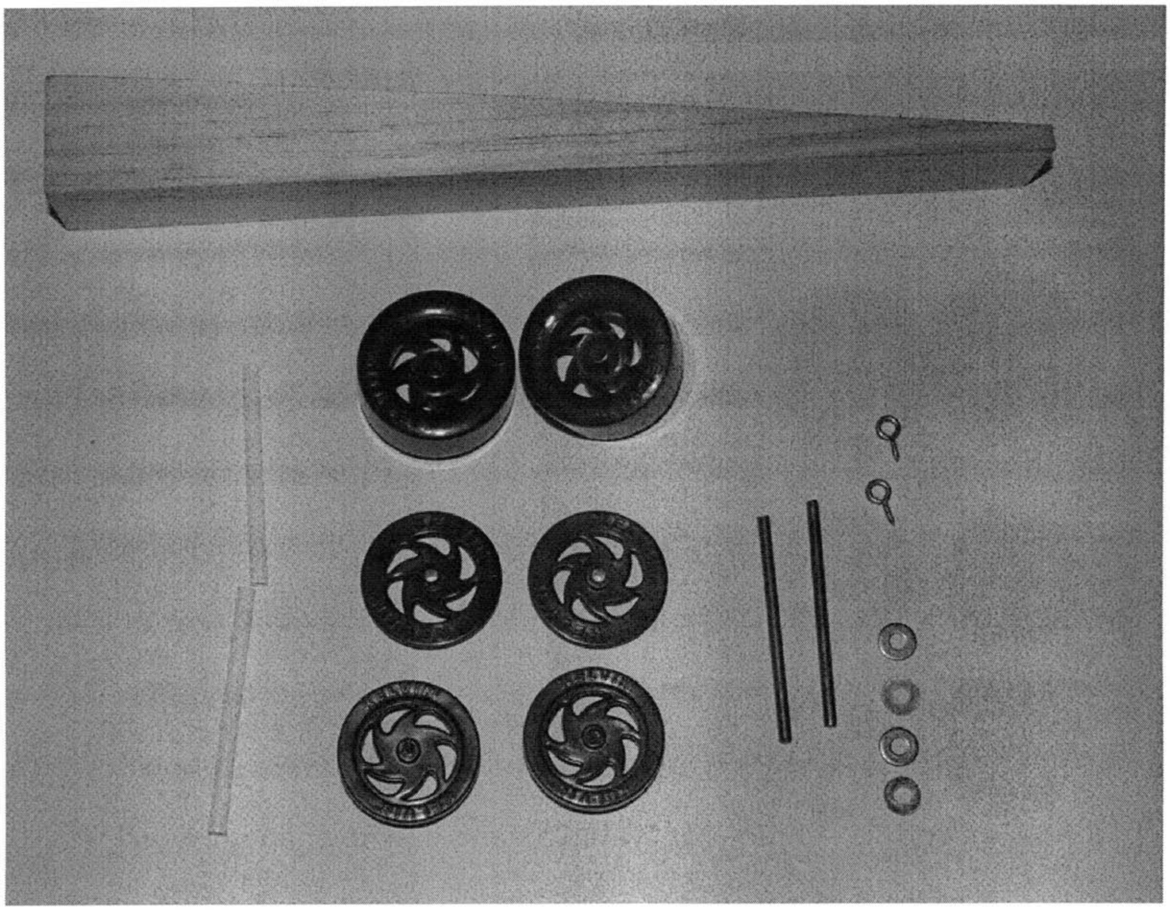


Figure 12: Car kit as received by students at onset of project

3. Tools available for fabrication

Students were allowed to use any tools available to them at home or in their shop classes. However, a drill press, band saw, wood rasps, sandpaper, and other basic tools were available to use in the classroom. Students were expected to operate all of the equipment themselves under the observation of a teacher. Figure 13 shows a student working on a band-saw to cut a rough shape into his car.

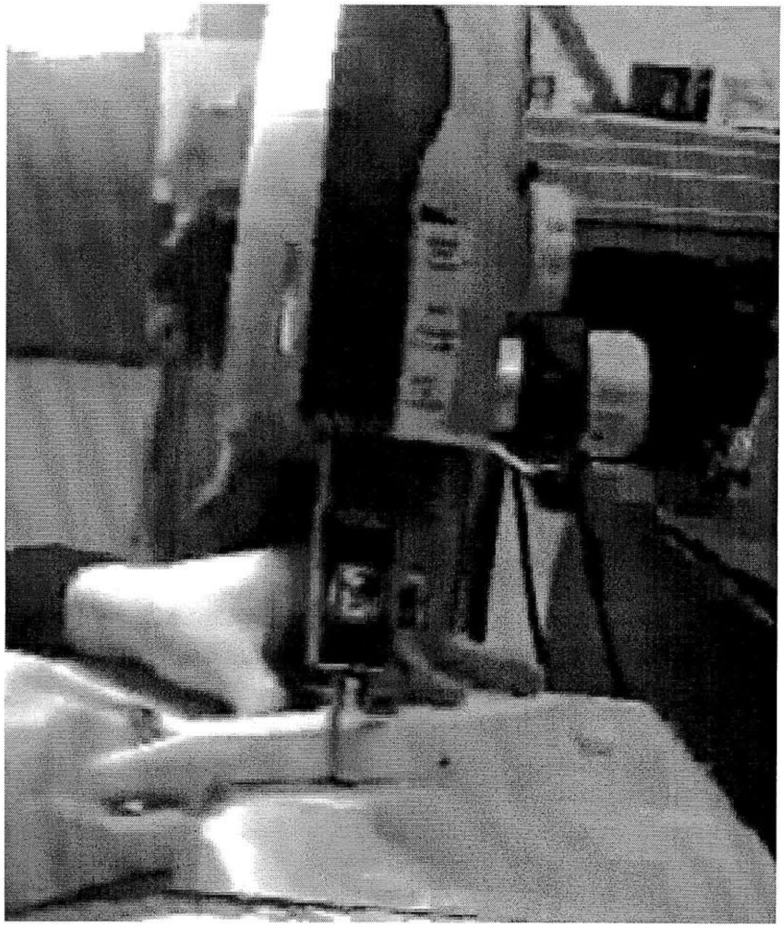


Figure 13: A student operates a band saw to shape his car

V. Project materials, workflow, and grading structure

1. Designing workflow

An old saying goes, "if you leave it till the last minute, it'll only take a minute." It is very challenging getting high school students to maintain a sustained work effort. If a whole project gets done in one night, it probably means the student didn't have a chance to grow through constructive feedback. Even if feedback is given at the end of a large of a project, chances are that a student will ignore it since from their viewpoint, the project is over and out of their life. Not only that, but the emphasis becomes only focused on the final product and not the process used to get there. This project emphasized mastering the process of design as opposed to the finished product. It was also assumed that students wouldn't do work unless something was due, since students tend to be very grade driven. Therefore, the project was designed to encourage a sustained work effort by incorporating weekly milestones called "design elements" that students had to submit every week.

The idea was that students would slowly hone the performance of their car by choosing (based on physics theory) what they would modify on their car following up with a full cycle of analysis, implementation, and testing. Students were encouraged to explore, even at the risk of failure, during intermediate weeks. However, it was also made clear to them that even though this was a safe time to learn, they still had to produce a functioning car by the final week. The element of project milestones was drawn from experiences in both 2.72 and 2.009. Both of these classes also tolerated both success and failure at certain times, but were very severe about the pressure of coming through when it mattered, which in all cases was the final presentation of the product.

2. Designing grading and student incentives

When designing the project, much consideration was given to the incentives that would encourage students to want to do well. Learning is a cooperative exercise between students and teachers, so it is absolutely critical that a teacher strives to understand the major factors that will get their students to play along with what they are trying to achieve. The two major incentives that were targeted for performance leverage were grades and the competitive spirit between teams.

It would be easy to set a team's grade proportional to their car's performance and the completeness of their work, however this creates an atmosphere that isn't conducive to testing, failing, and most importantly, learning from failure. The grading style of this project was something that the students apparently were not used to. The emphasis was on implementing the design process and attempting to apply physics to the best of their ability. So if they did those things, everybody had a chance to get 100%, even if they weren't getting all of the physics exactly right or if their car wasn't the fastest. This put the emphasis was on putting in the effort, implementing feedback, and thinking critically. In other words, it was expressed to the students that there was no penalty for failure, only for not trying. When grading the notebooks, completeness, thoughtfulness, and good scientific practice, is what was graded. I found that many students did everything they could to avoid actually using equations in their analysis, so I adjusted by placing a large emphasis of the grading on their theoretical predictions of vehicle performance based on their changes.

The second mode of student motivation leveraged was the natural propensity of teenagers to feel competitive towards their peers. There is a fine balance between a healthy level of team competition and a level that turns the class atmosphere negative. In 2.72, an urgent feeling of competition was leveraged from the final performance of the lathe. Instead of imposing penalties for ranking lower than first place, bonuses were awarded for doing well. A similar mentality was adopted for this project.

In 2.009, competition was also utilized to motivate students, but in a different way. After every major milestone, groups were openly ranked against each other, which made for some uncomfortable moments, but it definitely worked because no group wanted to finish last. This method came across as brutal, but there was evidence that it worked. It was not uncommon for the lowest ranked groups to come back and rank highly in the next milestone because they felt pressure to improve. By showing students their relative performance among classmates, they can more easily comprehend what the teacher is looking for because they are capable of cross-referencing their own performance and their own work's evaluation with other groups' performance and the respective evaluations that resulted. In the context of this project, a similar mode of peer pressure was instilled by publicly posting every team's weekly grade on a wall in the classroom. It was not uncommon to overhear students work out the aforementioned cross-referencing, which yielded some great moments of group reflection.

In addition to barrowing the modes of peer pressure defined above, I created additional elements that instigated a healthy feeling of competition. They are listed below:

- Had the current best speed always posted next to the track (with the group name that did it) so that students always had a benchmark of what speeds were possible to achieve. This value changed at least five times a day it seemed and the students really relished crossing out the old record-holder's name.
- Had different colored wheels that students could "earn" if they achieved certain vehicle speeds. This was much like showing rank on a military uniform and teams demonstrated great jubilation upon achieving them.
- Built my own car and made sure that I was always #1 – left the best students always wanting to beat me and do better. Indeed, it would be quite an accomplishment for a group of high school freshmen to beat an MIT Mechanical

Engineer (but it never happened)! I made sure to always beat the highest score by no more than 3-4mph so that the thought of beating me was always in reach.

- Showed students my car, but did not tell them how it worked or exactly what I changed. At least this pointed them in a good direction to look if they were getting stuck. The ultimate goal isn't to trick students, but the mystery challenged them to do better.

The overall combination of these factors proved to be highly effective. Not only was I surprised by how many students were working hard to submit quality work on time, but I saw almost every single group in an absolute frenzy at some point trying to beat their peers. Groups would come in at 7am or stay till 6pm at times just to get their name on the record-holder board for just a moment. All the girls wanted to beat all the boys and friends in different groups (and even different classes) would text each other to report their newest top speed. It was really great to see the boundary between hard work and hard play fade away, the power of allowing students to have some fun in school is so underrated.

3. Timeline for administering class materials and new sources of knowledge

Below is a week-by-week summary of what was done form an instructor's perspective. All resources cited here are in the Appendix section and represented much of the front-end preparation to running this project.

4. Week #1

1. Handed out project syllabus (Appendix A)
2. Delivered "How to Design" presentation (Appendix B) to equip students with frameworks for how to function as a team and execute steps of a Mechanical Engineering approach to design.
3. Handed out "How to Keep a Design Notebook" document (Appendix C)
4. Had students form groups and generate creative group names (allowed time for teams to bond)
5. Had students fill out individual role forms (Appendix D) and explained each role.
6. Re-emphasized the importance of individual contributions the team effort, clarified the peer-review (worth 10% of their grade) system to help motivate individual accountability.
7. Issued each group a blank design notebook.
8. Held a 5-minute brainstorming activity for teams to start thinking about what they think might be important to change.
9. Explained Assignment #1 that would be due the following week (seen at end of Appendix B).
10. Posted all materials delivered up to this point on the class website.

5. Week #2

1. Collected notebooks for grading of Assignment #1 and returned them the next day with feedback.
2. Made car kits available for sale for $5 a piece. Groups had to purchase 3 kits.

6. Week #3

1. Nothing done from instruction side. Group's given extra week to get their kits together and figure out how to approach Design Element #1

7. Week #4

1. Design Element #1 collected for grading.
2. Notebooks returned to groups the following day with feedback. Included a warning note (Appendix E) that told students that in general, they did not follow direction and so they should re-read the syllabus and "How to Design" presentation or face increased harshness in grading. Note was especially poignant because I had already started grading harshly without them knowing it, so the idea of me grading even harder was supposed to provide the "shock factor."
3. Made "Helpful Hints" document (Appendix F) available to groups 3 days before Design Element #2 due date.
4. Began beating other students with my own secret design car.

8. Week #5

1. Design Element #2 collected for grading.
2. Notebooks returned to groups within 2 days with feedback.

9. Week #6

1. Design Element #3 collected for grading.
2. Randomly generated single elimination racing brackets for each class.

3. Had each team present the highlights of their car to the class using their final car brochures as a guideline. Trash talking was allowed at this point to keep the final event fun.
4. Conducted final racing tournament based on racing brackets that were previously created.
5. Recognized the winners of each pool with a "certificate of grade-boost."
6. Conducted "most beautiful car" vote with students.
7. Handed out the final peer review form (Appendix G) for students to do alone as homework.
8. Computed and submitted final student grades.

10. Grading breakdown for each class

Every class was graded in the same way despite varying levels of background knowledge and student ability because grades were only dependent on completeness, lateness, grade-boosts within their own class, and the ability to follow procedures and directions. Figure 14 shows the distribution of grades for each class that participated. Note that the grade 12 students were already accepted into college at this point, so they may have cared a little less about their grades than the grade 9 students. In a way Figure 16 quantifies a term that describes this, known as "senioritis." Even though the grades don't necessarily reflect understanding of content knowledge, there is an unquantifiable correlation between student effort and their motivation to change in their misconceptions about physics. Therefore, student grade data is an important and relevant piece of information to consider when analyzing changes in their content knowledge and problem solving abilities.

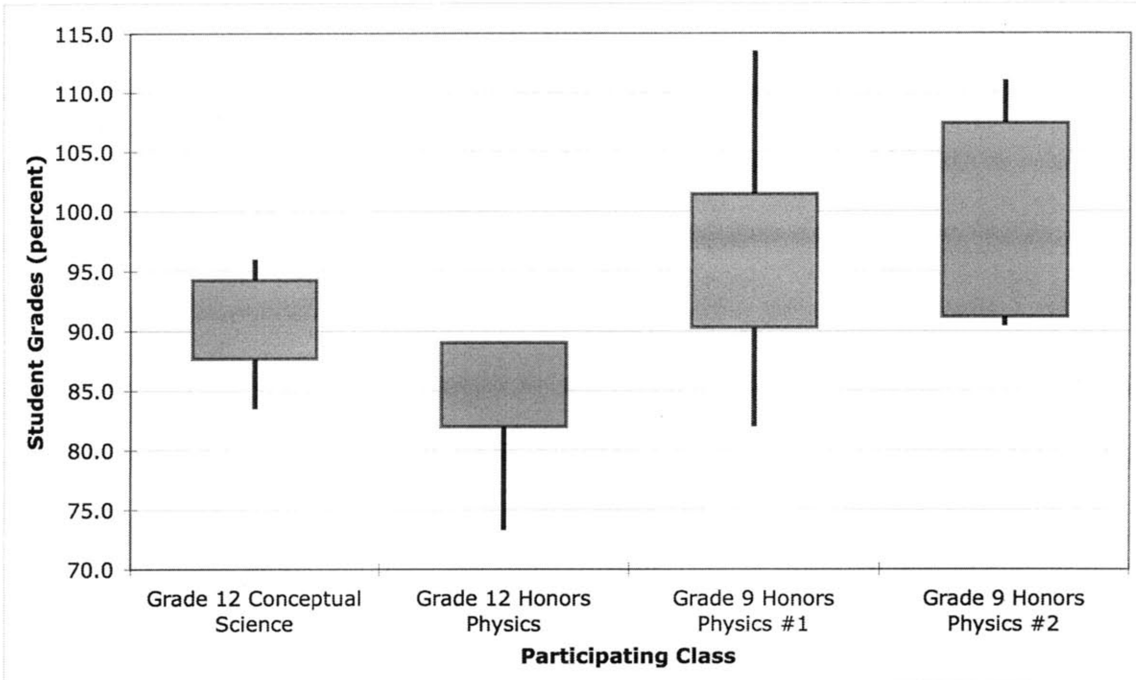


Figure 14: Distribution of individual student grades by class

VI. Analysis of student understanding and performance

1. Common misconceptions and gaps in learning exposed

The initial brainstorming activity revealed some very flawed understanding about the idea of optimization as well as the implications of things like aerodynamics, mass reduction, momentum, and energy principles. Later in the project, when students started getting into some more complex ideas like maximizing impulse from the launch system, more misconceptions were revealed about gas dynamics and transfer of energy types (i.e. moving between potential energy in the pressurized gas to kinetic energy of the car and frictional losses which result in heat energy). Every single group showed gaps in their physics knowledge, with the exception that stronger groups were showing gaps in more complex areas of understanding.

Two examples from the design notebooks (Figure 15) are used to illustrate some of the misconceptions unveiled during the initial brainstorm process. This brainstorming process was done directly after a long presentation on engineering, so some of the things like mass and friction were briefly mentioned. Most students recalled these from that instance, but may not have come up with it on their own. Additionally, I had already mentioned some important factors to change to the class that ran the first iteration of the project and I strongly suspect that word spread about what I said.

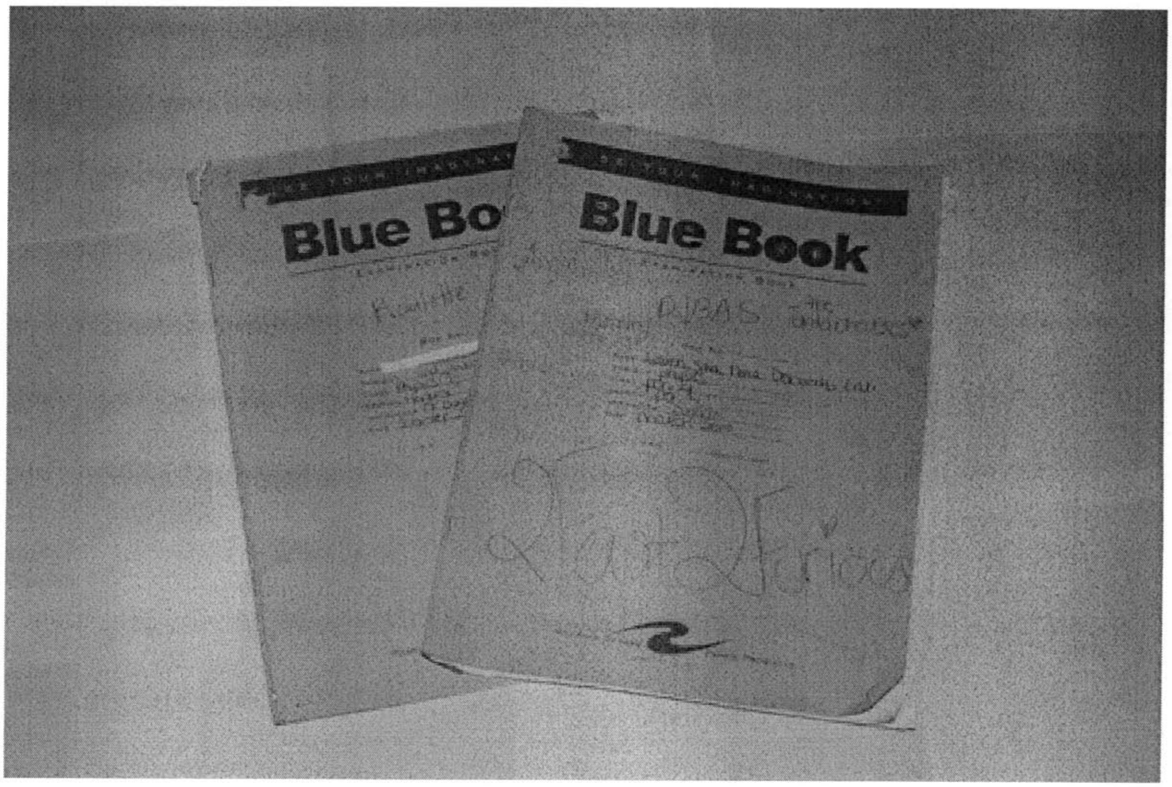


Figure 15: Design notebooks were a good place to observe misconceptions

In the "How to Design" (Appendix B) presentation, I warned students emphatically to stay focused on making their cars go faster as opposed to making them look as much like the real cars they see on the road. So many students avoided some of the more blatant suggestions such as adding spoilers or suspension, but as the brainstorming in Figure 16 shows, students were still struggling to separate the design objectives of road cars to those of their own.

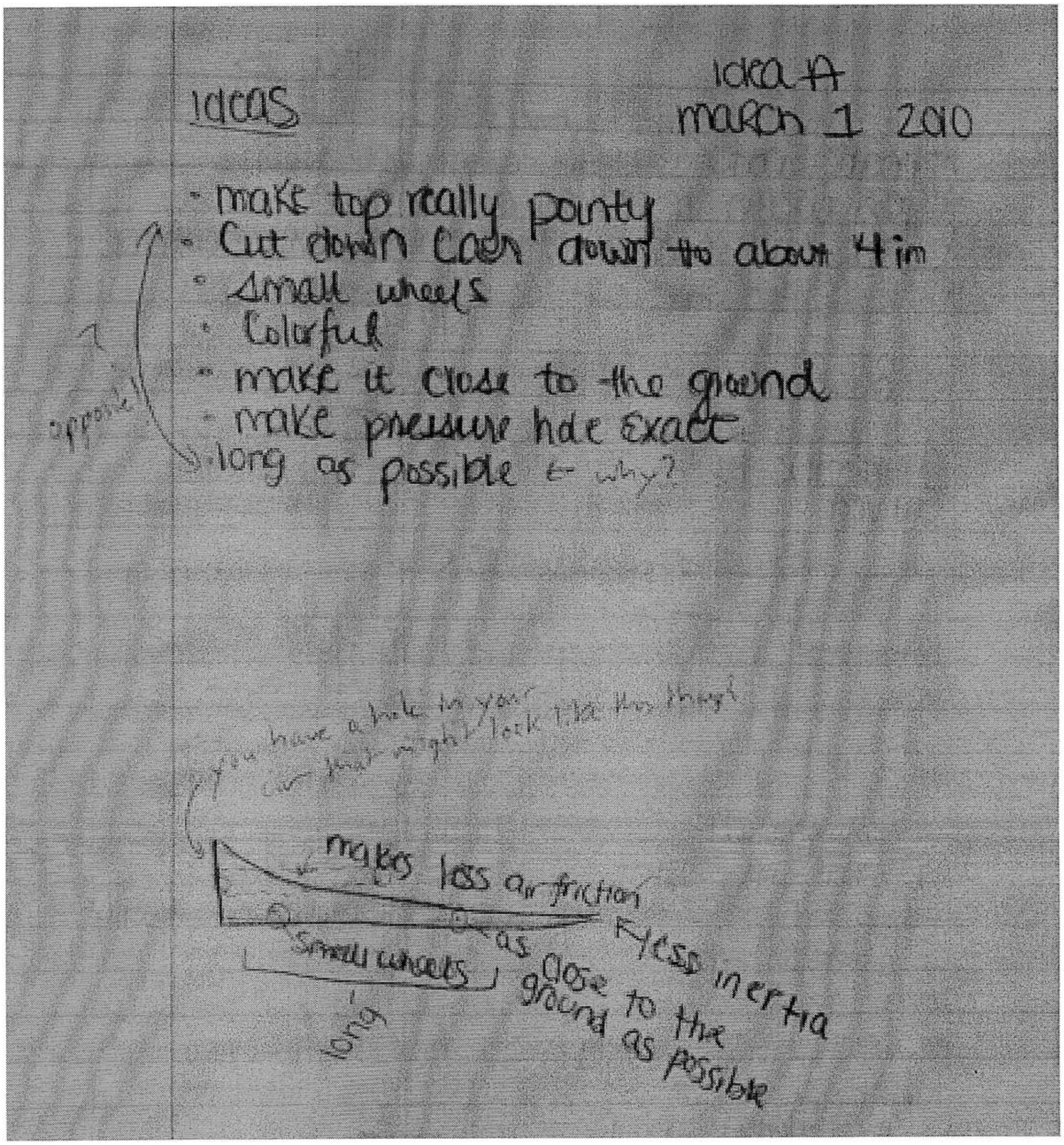


Figure 16: Example of student misconceptions #1

The student work in Figure 16 shows several choices that were made without good design basis.

1. "Cut down to about 4in." - How did they arrive at 4in? Do they understand the connection between car size and reduced mass? My hypothesis is that they didn't make this connection; instead, they probably saw my own car at some point, which was about 4in long.
2. "Make it close to the ground." – This looks like a misconception derived from the fact that some road cars ride as little as half an inch from the ground. Yet, the students appear not to appreciate the scientific basis for cars being that close to the ground. Cars that are low to the ground are taking advantage of the Bernoulli effect, creating a low-pressure zone under the car that pulls the car onto the road for better grip and thus better handling. My hope was that students would try to understand, either through previous knowledge or research, the effect of a change like this so that they could make the connection that their car doesn't need to have good handling characteristics (it doesn't turn, and it rides on a string) and ignore it.
3. "Long as possible." – This statement confirms that "Cut down to about 4in" was made without full understanding. It is my hypothesis that this group figured a car should be as long as possible because they are used to seeing long dragsters such as referred to in Figured 11. A long wheelbase typically leads to increased stability, but once again, their car rides on a string and so stability is not a concern. The only significant effect the length of their car had was either

increasing or decreasing mass, however this was not immediately apparent to all groups.

Another note to make about Figure 16 is that many groups struggled extensively with being specific with their ideas. For example, Figure 16 features the statement, "make the pressure hole exact." Exact in what dimension? Exact to what? Why make it exact at all? In cases like these, it was very unclear if these statements were made because the students still struggled with their communication skills in general, or if they were purposefully unspecific to hide their lack of understanding. The latter case tended to be truer when groups overheard other groups or myself talking about an effective change and decided to mention on the sole basis that they heard it from somewhere else.

Figure 17 shows another example of group brainstorming. This group seemed to have a stronger initial understanding of mass reduction, friction, and aerodynamics, but they still struggled to show mastery in more complex areas.

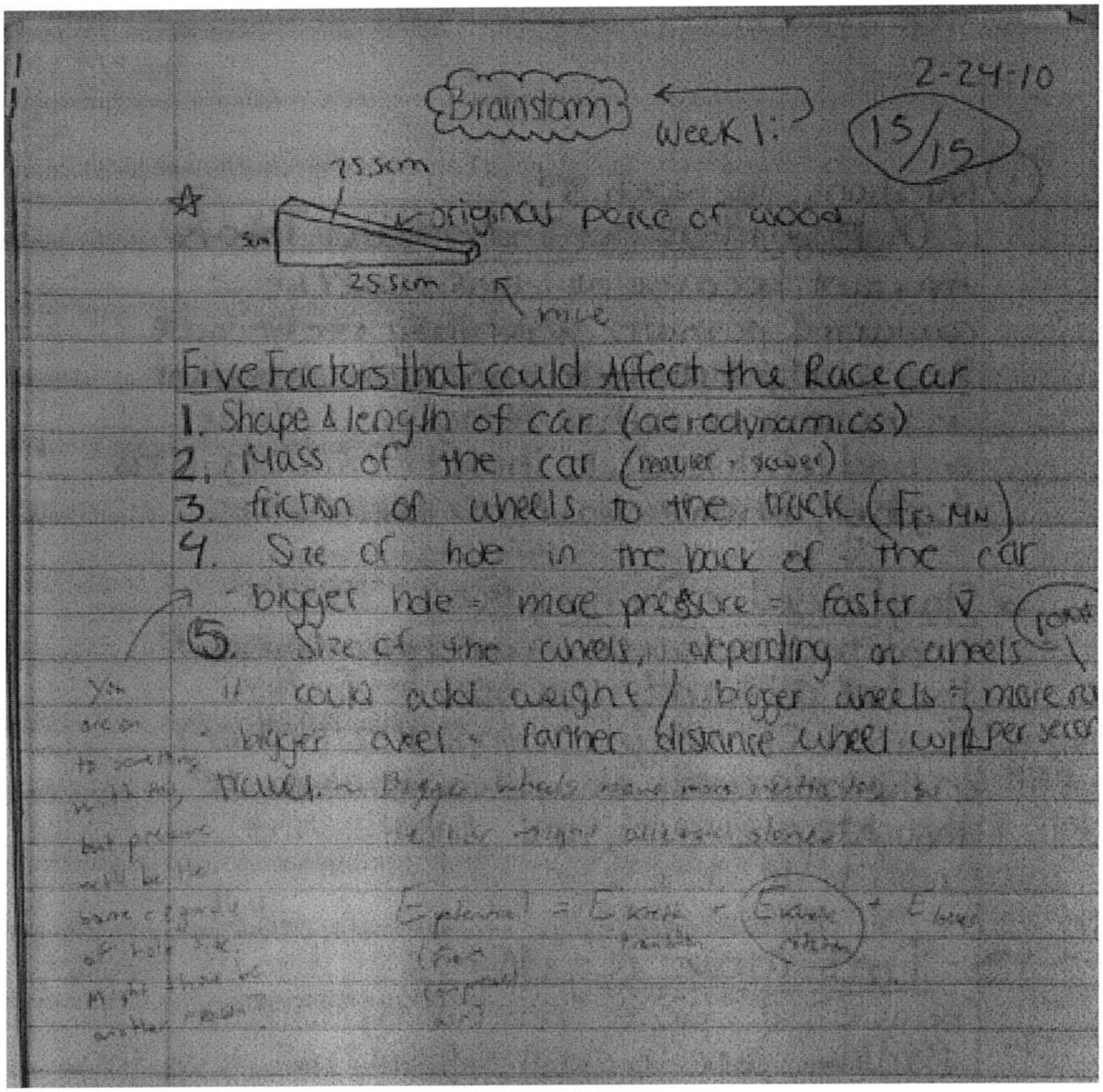


Figure 17: Example of student misconceptions #2

Their notes 1-3 show good understanding, they relate shape to aerodynamics, mass to speed, and friction with moving parts. The last two of their points still show some areas of misunderstanding.

1. "Size of the hole in the back of the car – bigger hole = more pressure = faster"

   – This group was more specific about how they were going to change the hole in the back of the car, but still not specific enough. Bigger in what dimension? Their major misunderstanding here comes from the link between pressure and force. It would have been nice if they would have specified the dimension that they wanted to make the hole larger in because if the hole was made deeper, they are changing the distance over which the pressure force acts, but if the diameter were bigger, they would be changing the magnitude of the force because a pressure multiplied by an area determines a force. Therefore it is hard to target exactly what they were thinking when they wrote this down. Misconceptions about this topic seemed to be one of the more prevalent ones. Many students seemed to think they could change the pressure coming out of the brass launch tubes just by changing the dimension of the hole in their car, they didn't understand that the only thing that was changing was the area and distance over wish the pressurized gas was acting on their car. Figure 18 shows a similar example of how one group thought that allowing air to leak out around the brass launch tube would actually increase pressure.

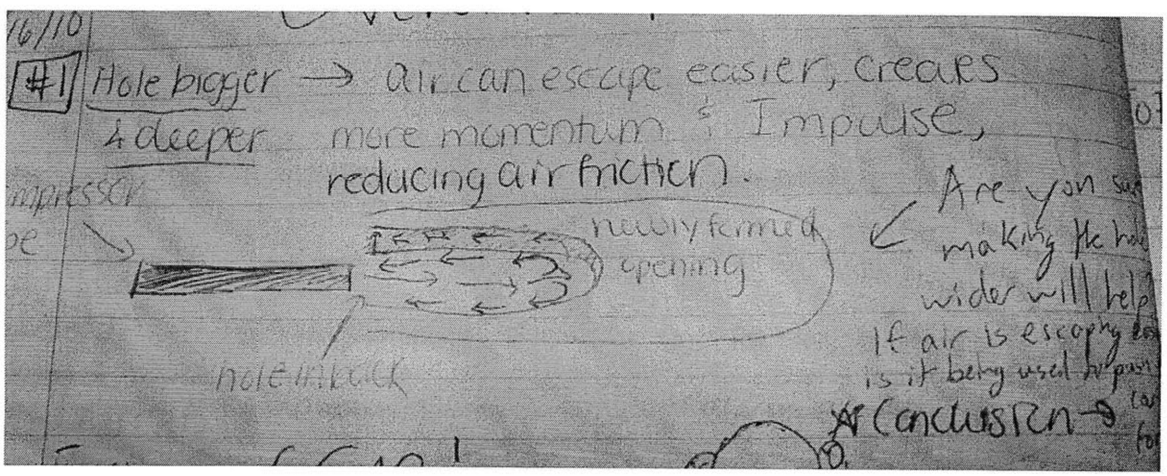


Figure 18: Misconception of how gas flow affects pressure

2. "Size of the wheels, depending on wheels it could add weight / bigger wheels = more rotation – bigger axle = farther distance wheel will move per second of travel." - Here, a group is getting it right and getting it wrong at the same time. Recognizing that smaller wheels reduce mass is a great start, but assuming that a bigger diameter wheel will result in higher vehicle speeds than a slightly smaller wheel also means that there is an assumption that the wheels are rotating at the same speed. This represents a misunderstanding about the broader concept of energy. The group demonstrated a good understanding of basic rotational kinetics, but picked the wrong situation to apply that piece of content knowledge. They key to understanding why the vehicle speed is largely independent of a wheel diameter is understanding that the work done on the car from the compressed gas will, for the most part, go into the kinetic energy of the moving car and frictional losses. Advanced students recognized (later into the project) that some potential energy from the compressed was turned into rotational energy in the wheels. Since a wheel's inertia is related to it's diameter for a given mass, it is true that smaller diameter wheels will allow the car to travel faster because less energy is wrapped up in the rotation of those smaller wheels, but this still does not mean a student should assume wheels will rotate at the same speed regardless of wheel diameter. Additionally, this difference only showed to be significant when students started reducing vehicle mass to the point where wheels weighed in excess of 50% of total vehicle weight, so it was more of a subtle point to consider at the onset of the project.

Sometimes the biggest misconceptions came out just by listening to students talk amongst each other, since many of them were afraid to write anything down in their notebook unless they were positive it was correct. When they talked, there appeared to be less inhibition that saying something wrong would lower their grade or make them look less intelligent. I had overheard students saying that they should actually increase the weight of their vehicle so that it picked up more momentum and speed as it moved down the (flat) track. This looks like another misunderstanding of energy conservation as well as Newton's basic laws. How could a car accelerate in the forward direction if there are no forces acting on it with a component in that direction? How does an object increase kinetic energy without positive work being done to it? Those are questions they should have been able to answer correctly given the curriculum they had been through, but they weren't able to apply these key concepts to this real situation of a car running down a track. Once again, these are just examples, but it goes to show how effective this project was in testing for true understanding of the material they had supposedly learned previously in the class. Every single group showed a gap in knowledge at some point, but hopefully that also meant that every single group was able to learn something new or correct old misunderstandings at some point throughout the project.

2. Connecting equations and theories to the real world

One of the objectives of this project was to get students to realize that there is a connection between the problems in their textbook and real mechanical systems like their car. To do that, students needed to understand how to take their car, and model in it in such a way that they could apply the equations they knew to their model (which should look similar to the problems they are used to seeing in a textbook). Figures 19 and 20 show how students tried to model the effect of friction between the axles of their car and the body of their car. It looks like the group from Figure 19 had a better and more detailed model of what was going on, but the group in Figure 20 was still on the right track.

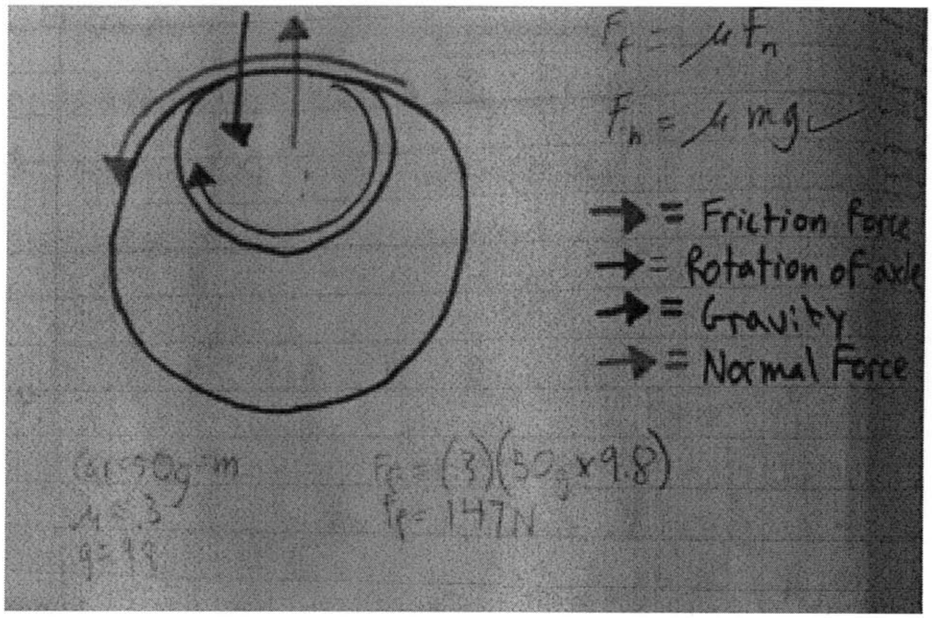


Figure 19: Model of axle friction #1

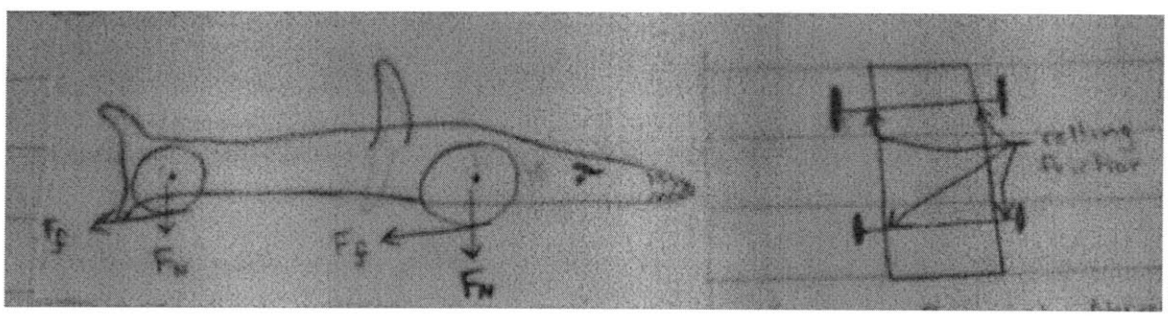


Figure 20: Model of axle friction #2

In general, students were able to model things that involved mass, speed, and friction fine. Students eventually learned to be specific about what they were changing so that their calculations reflected accuracy. Figure 21 shows the level of modeling that most groups started out with, and Figure 22 shows the detail groups were finishing with.

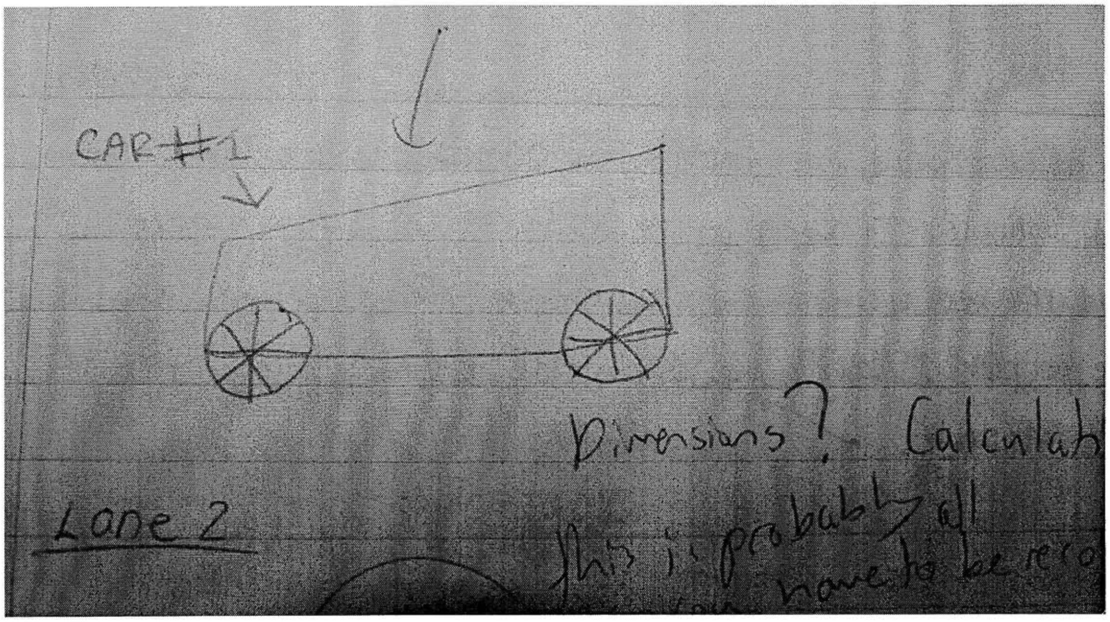


Figure 21: Example of unspecific modeling common at onset of project

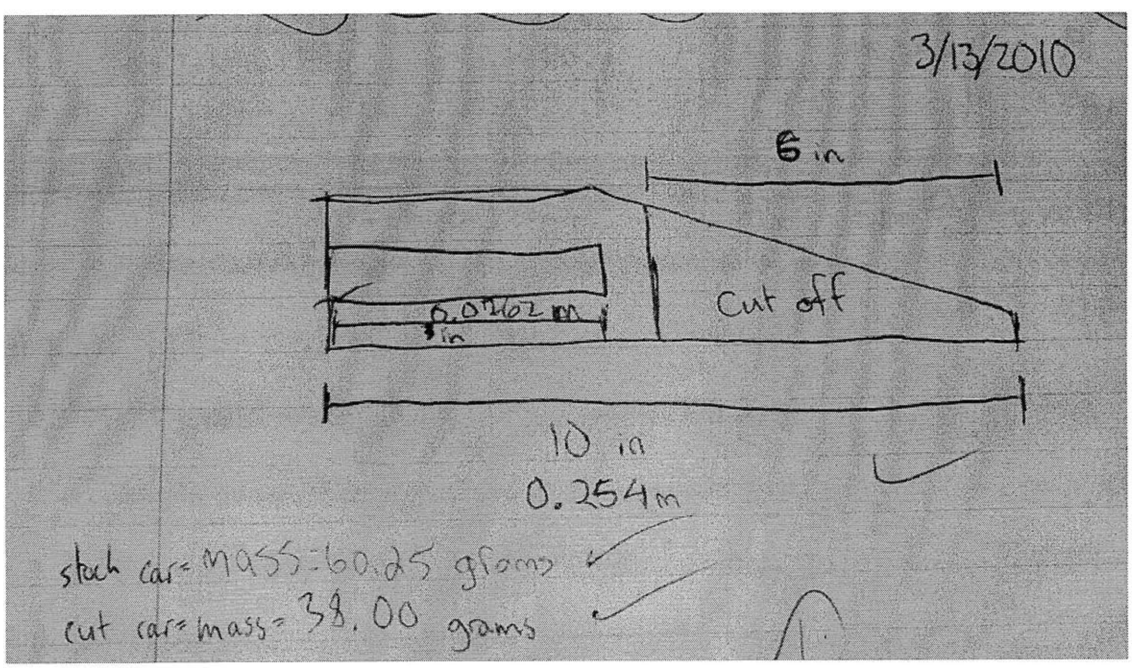


Figure 22: Example of good specific modeling of car dimensions

When asked to do calculations, many groups initially only provided answers in variables. This showed me that they were uncomfortable and/or too lazy to find actual numbers to replace those variables with. They were hit hard with poor grades for failing to at least attempt this step, but eventually learned that if they wanted to fill in a number for the "m" that stands for mass, they had to walk over to a scale and measure their car. This was the most basic type of connection between variables on paper and that variable's significance in the real world that was grasped by most students. Figure 23 shows a student at the moment of this revelation.

Figure 23: A student tries to fill in a mass variable with measured data

Students did begin to struggle when playing around with more complex examples. Figure 24 shows a group that tries to calculate aerodynamic drag using the actual dimensions of their car. One of the variables in the drag equation is "A" which stands for an area, but which area? Is it the total surface area of the car or is it just the frontal area? Is it the area only on the parts of the car that don't look aerodynamic? I had this group do an internet search to work it out and in the end, they successfully bridged the gap between an internet article describing drag and the actual dimensions it applied to on their car. Note that they were also able to figure out that the "ρ" in the equation stood for the density of air (and not the density of their car). This was the only group that attempted this calculation, so relatively, it was very high-level science they were doing.

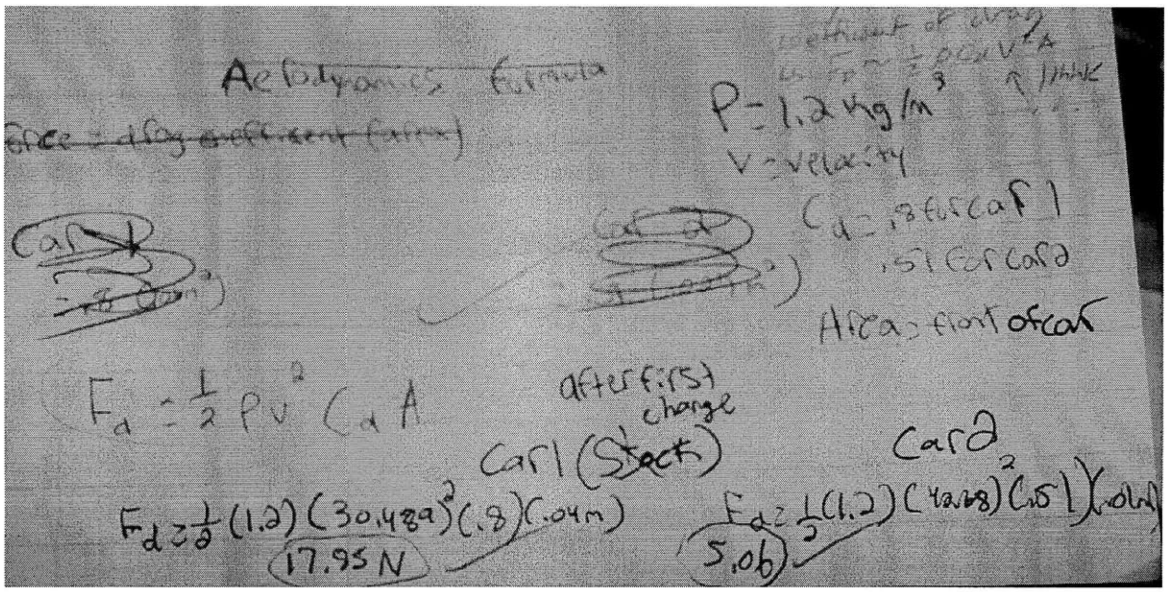


Figure 24: One group attempted a high-level aerodynamics calculation

One of the areas that students struggled most with on a broader scale was figuring out the total energy they had available for their cars. The idea of using work and energy to predict the speed of a vehicle was emphasized to most groups since they could incorporate several factors such as friction loss, drag loss, effect of mass changes and effect of launch hole changes into one equation. All they had to know was the mass of their car (which they could weigh) the magnitude of positive or negative forces (which they could calculate from modeling or testing) and the distance over which those forces acted (either the length of the track for friction and drag forces or the length of the brass launch tube that was inserted into their car for the positive pressure force). The general relationship between energy and either positive work was something that students struggled with though. As Figure 25 shows however, students began to make that connection.

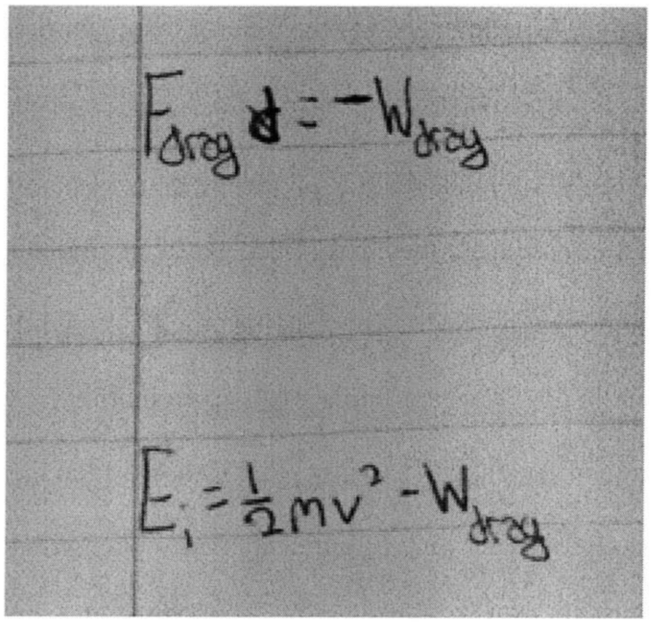


Figure 25: A group correctly utilizes the work energy principle

To find the initial energy, groups eventually discovered two options.

1. They could experimentally determine this value by running their car down a track to get its velocity and then weigh their car to get its mass. With those two variables, a value for the kinetic energy could be determined and if groups were willing to ignore non-conservative losses on their car, they could assume

this was equivalent to the total energy the launch system was delivering to their car.

2. They could calculate the force acting in their car from the launch tube by multiplying the pressure in the launch system by the area of the launch hole bored into their car. Then they could multiply this force by the distance it acted over by measuring the depth that the launch tube fit into the back of their car, this gives the total positive work done on their car which would be turned into the kinetic energy of their car or lost to work done by non-conservative forces.

In either case, students struggled to figure these things out on their own. When asked over which distance the force from the compressed gas acted on their car, most students stared blankly or replied that it was the entire 24ft of the track. I did step in on this area to help them out. Figure 26 shows a group's work in beginning to exploring this idea of impulse, the next stage of which was to realize that if they drilled the hole in their cars deeper, they could have a higher value of initial energy to play with. Most groups ended up picking this as one of their design elements to play with and many more found it to be the single greatest change they made on their car.

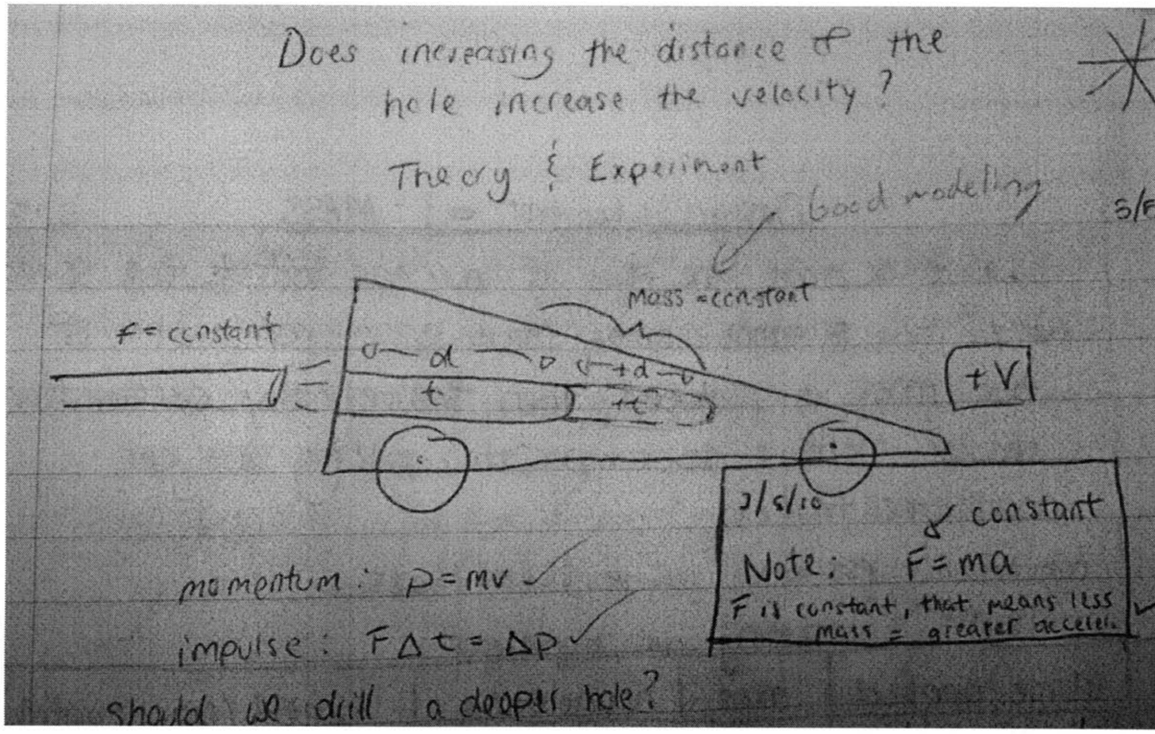


Figure 26: A group explores the idea of impulse after embracing the work energy principle

3. Does that make sense? - Working with math, unit conversions, and orders of magnitude

Even if students began to gain an intuition for which physics principles and equations were applicable in a given circumstance, there was a strong lack of intuition for the magnitudes of their answers. Figure 27 shows how a group concluded that their car had 68,344J of work done to it by the launch system. They may not realize it, but that would be near the equivalent of having a weightless 100hp engine stuck in their 30g car for an entire second.

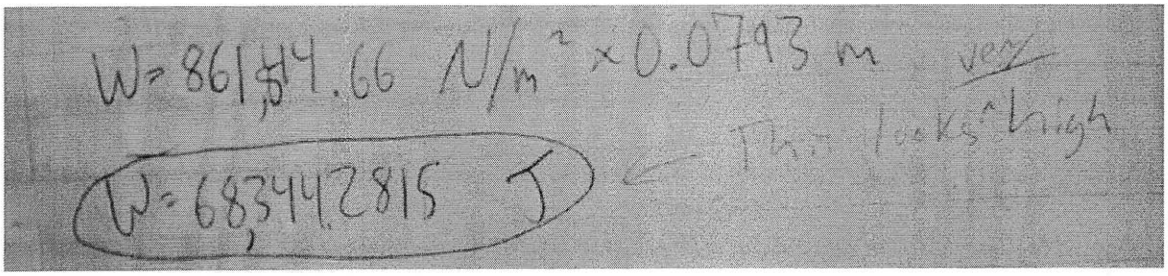


Figure 27: A group fails to appreciate the magnitude of an answer

This mistake was expected—high school students don't have many hands-on opportunities to gain the sort of intuition of one would need to realize this answer was a little high. However, the high value they calculated probably came from another mistake they probably could have avoided earlier in their calculations. It was not uncommon to see a student forget to change from psi to Pa for pressure, or from g to kg for their car's mass. Working in SI units was encouraged, but many students just forgot to do it and so their answers turned out wildly wrong. Through feedback in the notebooks, I encouraged students to reflect on this aspect of their answers before accepting them as correct. Figure 28 shows an example of this.

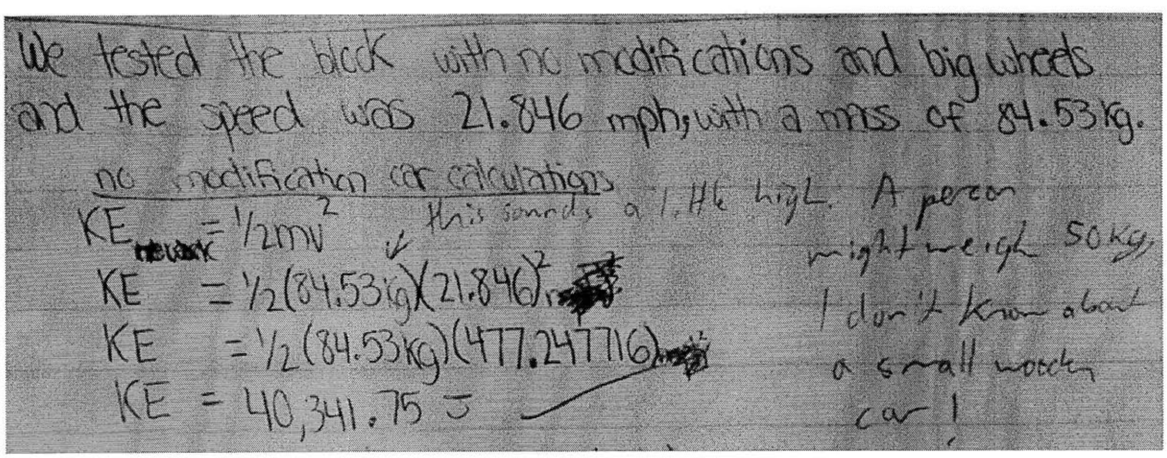


Figure 28: A group states that their model car weighs 84kg

Another common mistake students committed were basic math mistakes, especially with unit conversions. This is something that was generally picked up by looking at the magnitude of their answers. Some students seemed to especially struggle with the concept of applying math to variables, but the ones who got it were best equipped to manipulate and understand equations at a level that facilitated their ability to optimize their cars using those equations.

4. Breaking the ice: instigating creativity

This goes back to the idea of exposing students to open ended questions. They had a set of rules to follow, but nowhere in the rules did it say the cars had to be any shape, any size, or even have any number of wheels. As high school students it is hard to expect them to move directly to the optimal solution, so I used my own vision for Mechanical Engineering to help them along at times. Without any prompting for creativity, every car looked like the one shown in Figure 29.

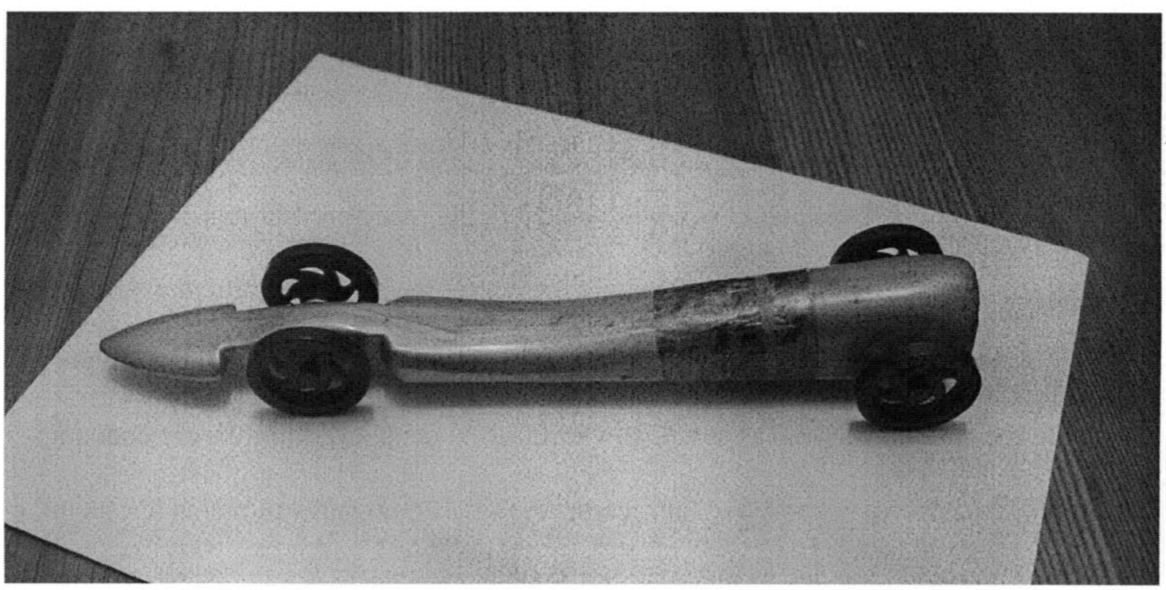


Figure 29: Typical look of the cars before groups saw they could do more

In order to open their minds a little bit, I revealed my own secret car to them. The top speed of this car was double the speed of their stock car, maxing out at around 55mph. This car is shown in Figure 30.

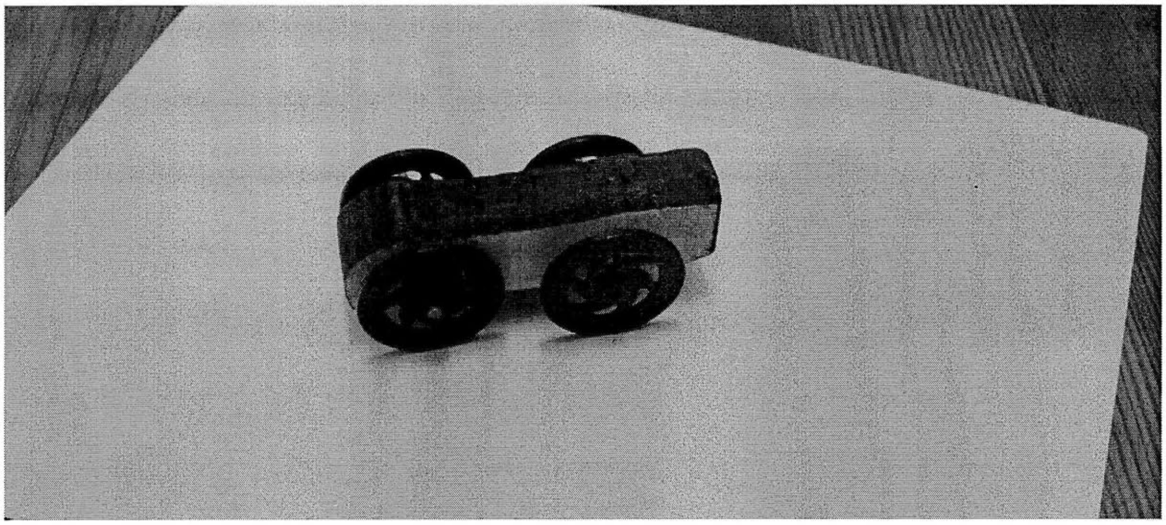


Figure 30: My own car was revealed one week in to help spark ideas

My own car heavily utilized weight reduction as well as maximization of impulse the car received from the brass launch tube. Other more subtle modifications were done such as lowering the eye-hooks to reduce friction with the fishing line and removing the recommended washers, as they only seemed to add friction and weight. This would not be the end of it though, as later cars would almost double the speed of this car. I let students see the car though, and it helped get them over the misconception that their car had to look like the one on the Kelvin racetrack instruction manual. The most obvious change to the car was that it was small, so within a few days, everybody's car ended up looking like the one in Figure 31. Their cars were small now, but still not as fast as mine because they hadn't picked up on the more subtle changes yet.

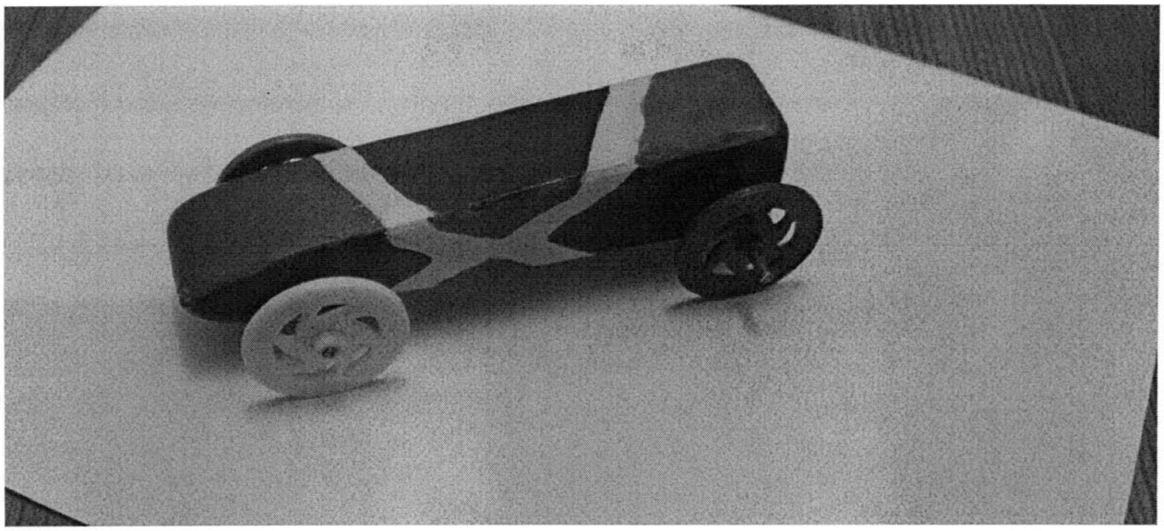


Figure 31: The trend of making a small car caught on quickly

Even though students were usually behind me on the more cutting edge ideas, they were still able to learn by trying to figure out what I had changed, and why it made a difference. In fact, I think that trying to solve the mystery of my car added motivation and excitement to the project for them. As always, any source of student motivation has to be taken full advantage of. Another major breakthrough in speed happened when I raced my car without a front set of wheels because they broke off in a previous run. The idea that the car ran much faster without them was something that even I didn't anticipate. However, upon reviewing the rules we all agreed that it didn't say anywhere that the car had to have any specific numbers of wheels. Within a day or two of that happening, most people were running their cars like the one shown in Figure 32.

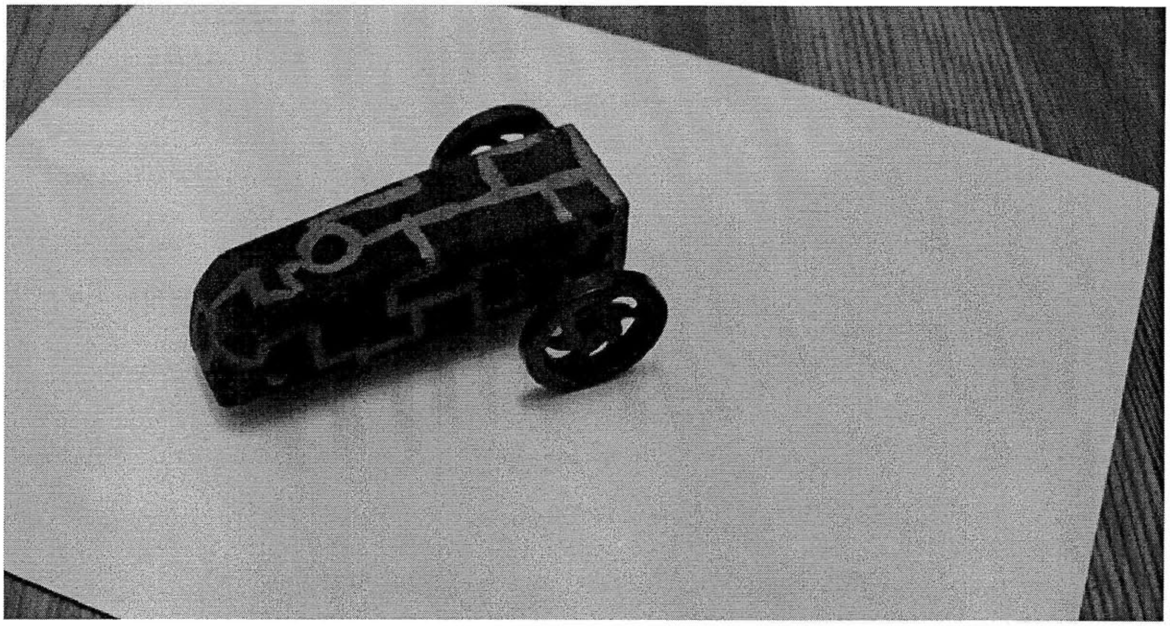


Figure 32: Breakthrough, students realize car doesn't need 4 wheels

This really helped students consider the fact that they could take advantage of other loopholes in the rules. At this point, groups started stepping up the creativity. Figures 33 and 34 demonstrate how students started to look at the rules as opportunities to explore creative ideas instead. The following excerpt was taken from the design notebook image referenced in Figure 33, "There are no rules stating that the front wheels must start on the track, nor does it give us an unfair advantage. If anything, having the wheels off the ground makes the string pull down on the car as it takes off, and therefore slows it down."

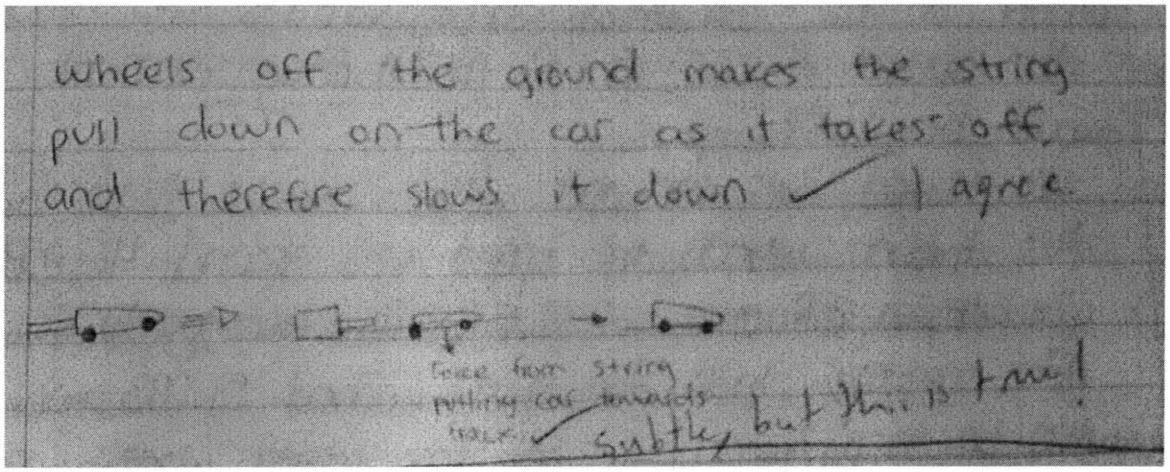


Figure 33: A group starts to look for creative solutions on its own

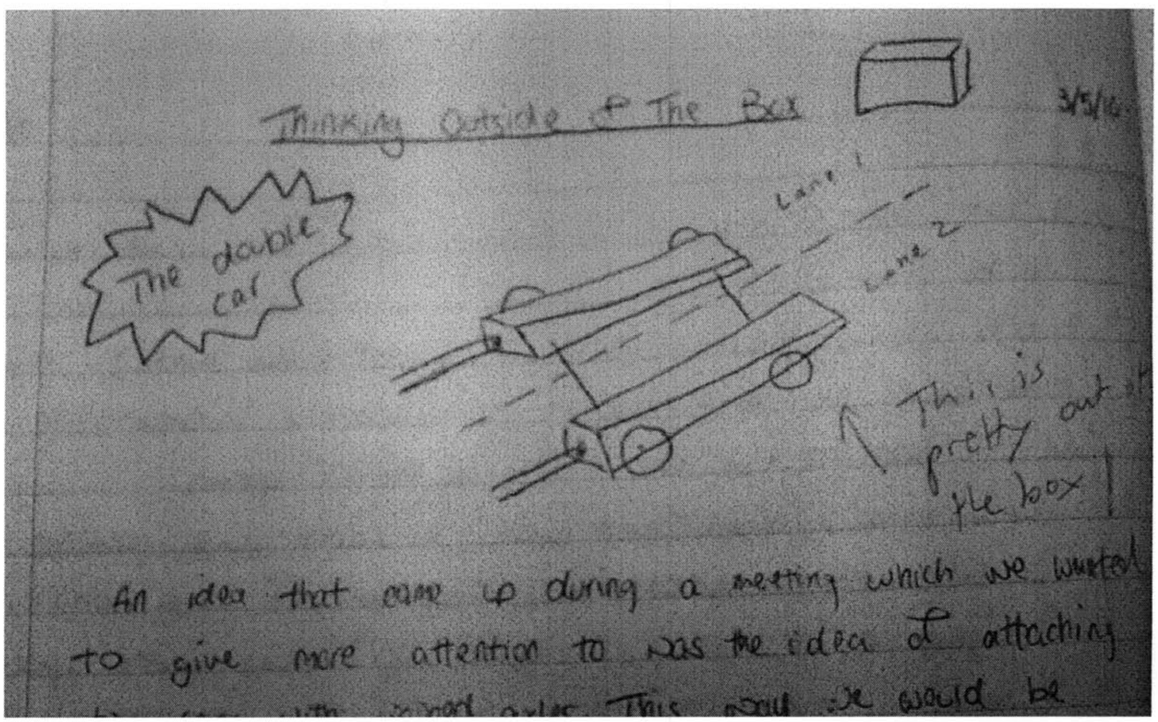


Figure 34: Another example of a group seeking creative solutions

Finally, I wanted to see how far I could stretch the students' minds with the notion of what their car could be, so I built the following car (Figure 35, not actual car built at the time, actual car was destroyed in testing) that featured no wheels at all. This car was built to show them that any part in their kit could be used for any purpose. Skis made out of the straw in their kits replaced the rear wheels. This car was running speeds of around 85mph.

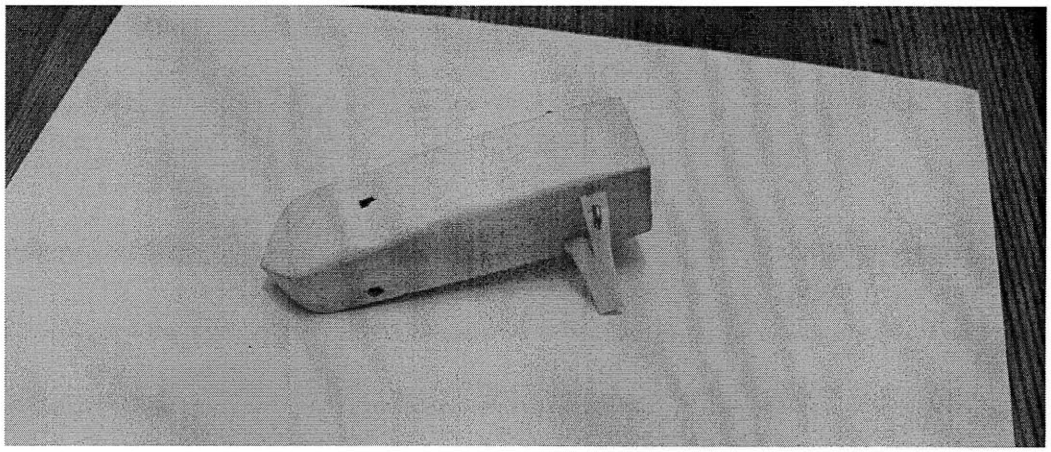


Figure 35: The first iteration of a car with no wheels

This prompted students to develop the design shown in Figure 36 (car shown was the fastest car developed in any class). These are the cars that were running in excess of 95mph. Some students argued that these were no longer cars, but they could not argue with the fact that it was a creative interpretation of the open-ended rules.

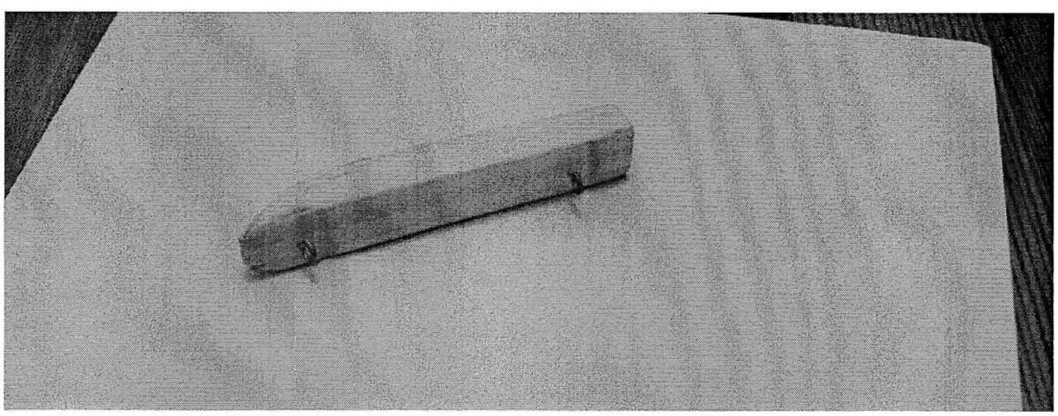


Figure 36: The fastest car developed, optimized in almost every way

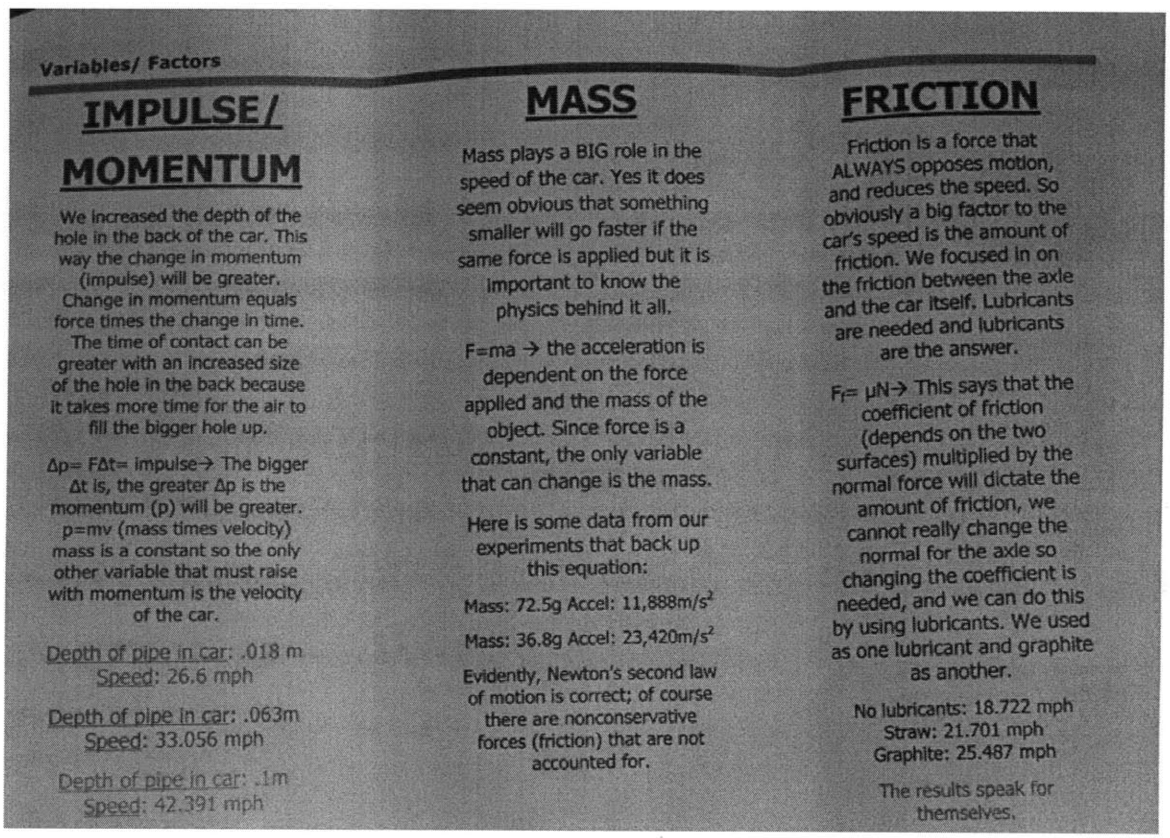
They say you can't teach creativity, but by showing them that there was no limit to what they could do as long as it met the basic rules of the competition, it seemed to change their perspective on how to approach open-ended problems like the one posed in this project. The final iteration of many group's cars had moved very far away from their initial iterations. It appeared as if they really started to appreciate the fact that different design objectives and constraints could lead to very different end products. Their final product was called a car, but so are the cars they see on the street. Yet, both examples were optimized for their unique purpose. This type of learning can't be taught in textbooks and was an absolute triumph of the project in the eyes of myself and the other science teachers involved.

5. Students implement changes, but struggle to explain why

It was evident that most students were looking to other groups for inspiration and a competitive advantage. It wasn't uncommon to find groups drilling the hole in the backs of their cars deeper or removing wheels without knowing why it would help. As a teacher, it was my role to ask that question, why? Even if students made a change before really understanding the science behind it, it was still a useful experience to draw understanding from. The information leakage between groups was a large source of uncertainty in the success in the project, so even though most cars looked fairly optimized by the end of the project, a certain percent of groups got to that point without full understanding of what they did. That is not to say that every group didn't learn something new in the processes, but it made it hard to evaluate the level of content knowledge each group left with.

6. Major areas of student growth – Content Knowledge

The major areas of growth of physics content occurred in the understanding of energy, work, mass, and friction. Figure 37 shows a group's summarization of how they applied these concepts to their cars. This particular group did not have a good grasp of these concepts at the onset of the project.



Variables/ Factors

IMPULSE/ MOMENTUM

We increased the depth of the hole in the back of the car. This way the change in momentum (impulse) will be greater. Change in momentum equals force times the change in time. The time of contact can be greater with an increased size of the hole in the back because it takes more time for the air to fill the bigger hole up.

Δp= FΔt= impulse→ The bigger Δt is, the greater Δp is the momentum (p) will be greater. p=mv (mass times velocity) mass is a constant so the only other variable that must raise with momentum is the velocity of the car.

Depth of pipe in car: .018 m
Speed: 26.6 mph

Depth of pipe in car: .063m
Speed: 33.056 mph

Depth of pipe in car: .1m
Speed: 42.391 mph

MASS

Mass plays a BIG role in the speed of the car. Yes it does seem obvious that something smaller will go faster if the same force is applied but it is important to know the physics behind it all.

F=ma → the acceleration is dependent on the force applied and the mass of the object. Since force is a constant, the only variable that can change is the mass.

Here is some data from our experiments that back up this equation:

Mass: 72.5g Accel: 11,888m/s²

Mass: 36.8g Accel: 23,420m/s²

Evidently, Newton's second law of motion is correct; of course there are nonconservative forces (friction) that are not accounted for.

FRICTION

Friction is a force that ALWAYS opposes motion, and reduces the speed. So obviously a big factor to the car's speed is the amount of friction. We focused in on the friction between the axle and the car itself. Lubricants are needed and lubricants are the answer.

Ff= μN→ This says that the coefficient of friction (depends on the two surfaces) multiplied by the normal force will dictate the amount of friction, we cannot really change the normal for the axle so changing the coefficient is needed, and we can do this by using lubricants. We used as one lubricant and graphite as another.

No lubricants: 18.722 mph
Straw: 21.701 mph
Graphite: 25.487 mph

The results speak for themselves.

Figure 37: A common summarization of student learning

Figure 37 shows a group that left with a strong understanding of some higher-level applications of the work energy principle. On the other hand, however, some groups were only able to take away mastery in more simple concepts like mass reduction. Figures 38 and 39 show how a group showed growth in the areas of friction and mass reduction, but failed to master the concept of impulse and work despite having used it on their car.

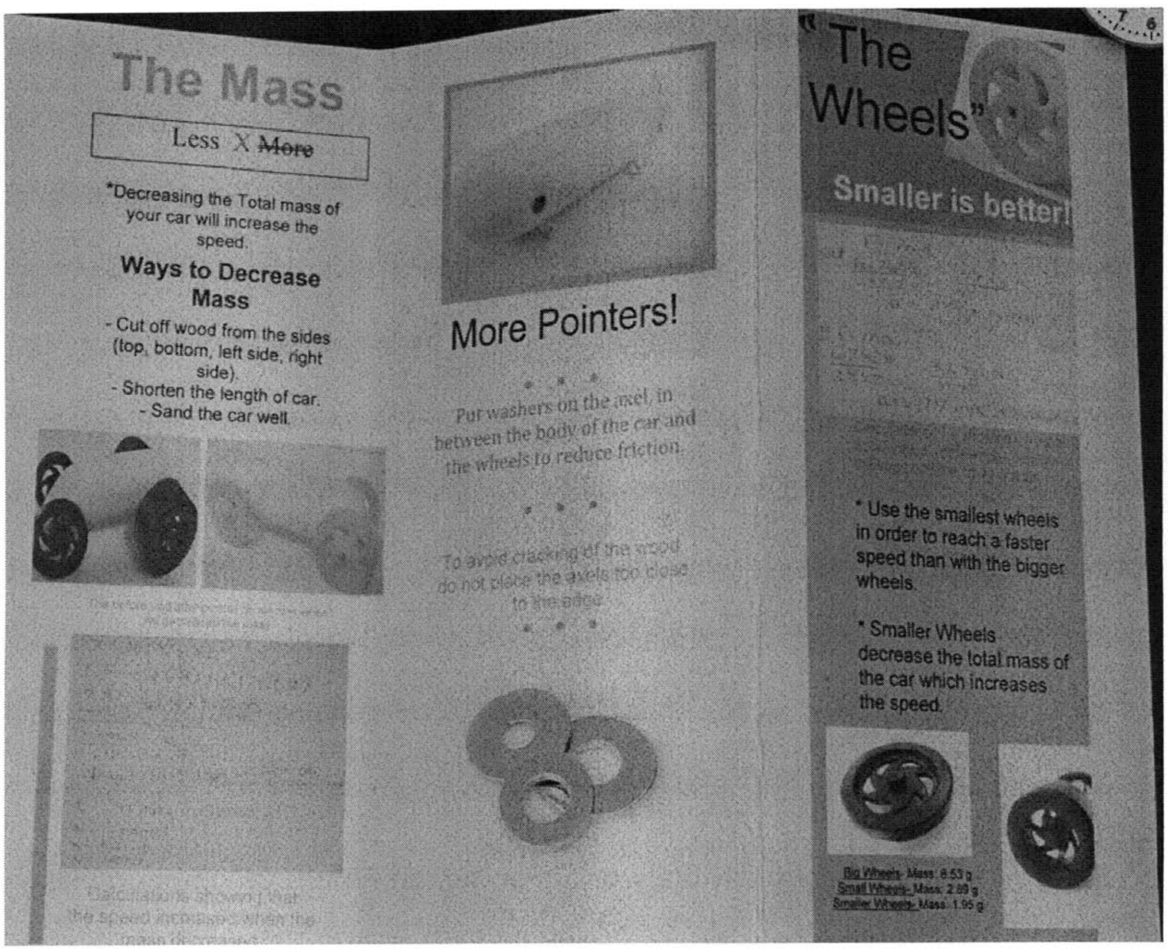


Figure 38: A group masters mass and friction reduction

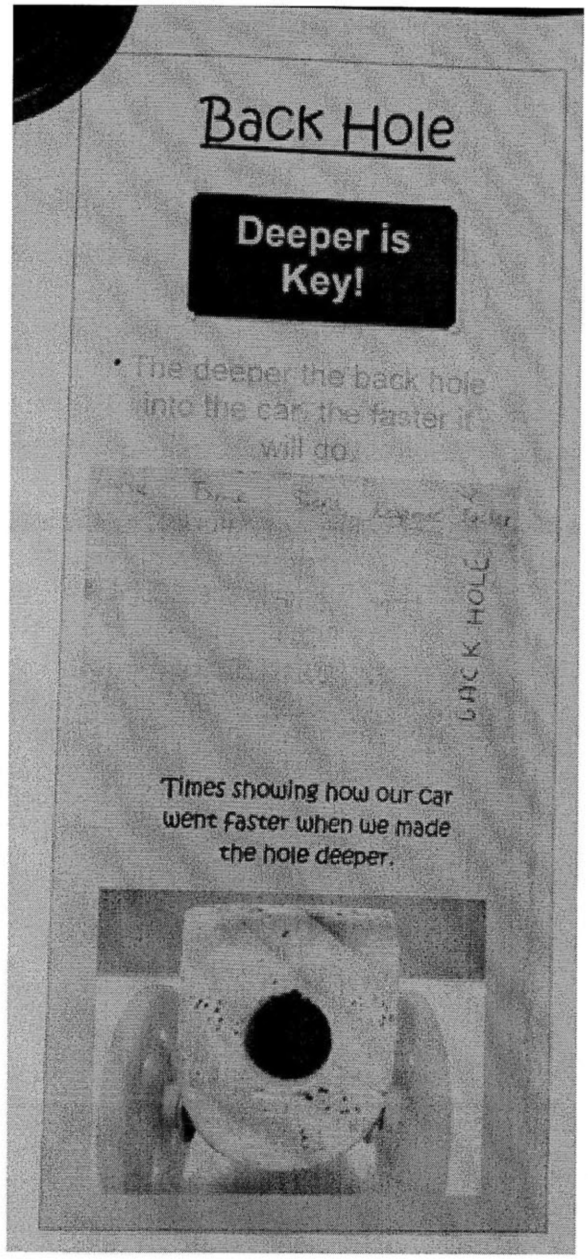


Figure 39: Same group (who's work is shown in Figure 38) implements design that maximizes impulse, but fails to explain it well

In addition to understanding the effects of applying scientific principles to their cars, some students seemed to gain a physical appreciation for how significant each factor was on their car. Figure 40 shows how a group mapped out the changes they made to their car versus how much speed increase they saw for each change. This sort of intuition can only be gained by working with real systems, thus reinforcing how important it is for students to be exposed to projects like this.

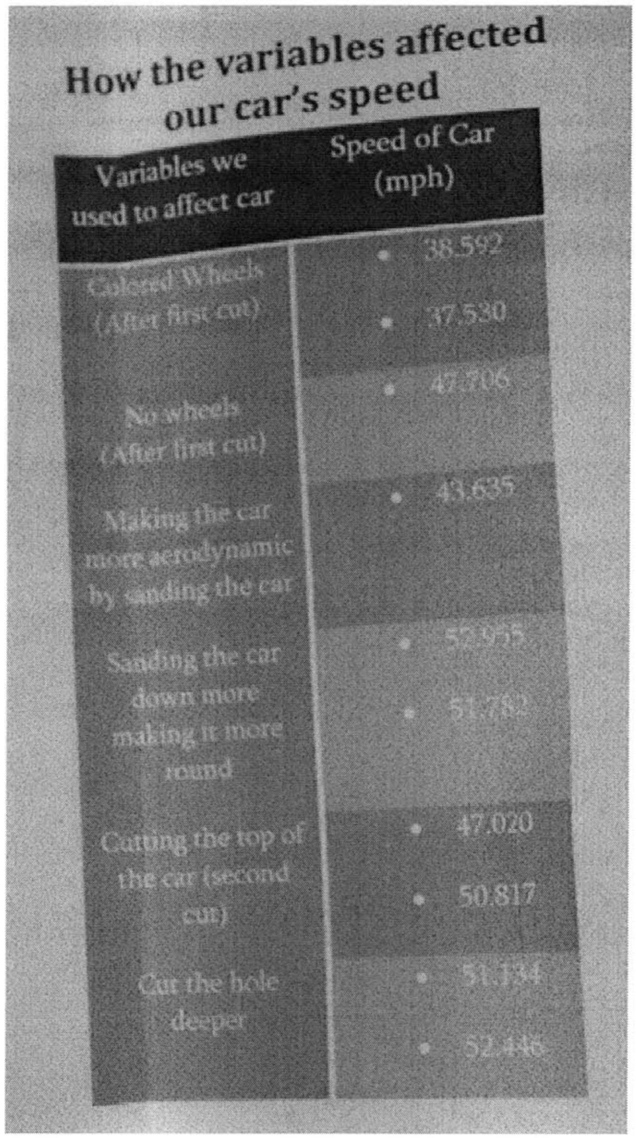


Figure 40: Students gain intuition for a design change's impact on performance by mapping out intermittent results

7. Major areas of student growth continued – teamwork, time management, emphasis on process, spatial reasoning, fabrication techniques, and the idea of balanced optimization (other attributes of a good engineer)

Although this project was designed to help expose and correct student misconceptions about content knowledge, many students expressed that they grew much more in other areas. For many students, this was the first time they've been asked to design their own experiments and work effectively in a group environment.

Most groups struggled initially with implementing the scientific process. Namely, the idea that only one variable can be tested at a time so that changes in performance could be correlated correctly to the changes they made. After the first Design Element was due, a large majority of groups came in with a near finished car where they had made changes to the shape, size, wheels, and axles all at one time. Through tough grading and verbal reinforcement, this began to change. Groups showed lots of growth in their ability to design thoughtful experiments and carry out thoughtful and organized testing. Figure 41 shows how a group came up with a smart solution to test the effect of removing the straw bearing from their car without doing any actual track testing.

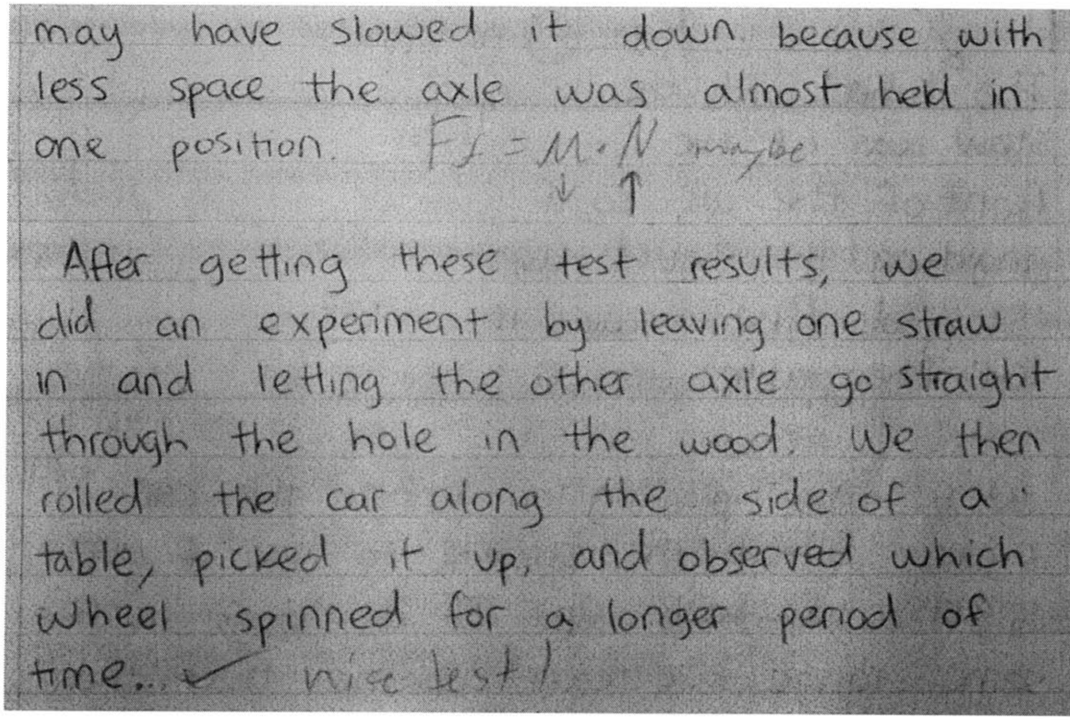


Figure 41: Students learn to design their own experiments

Figure 42 shows a group doing some very systematic testing of a similar variable, axle friction.

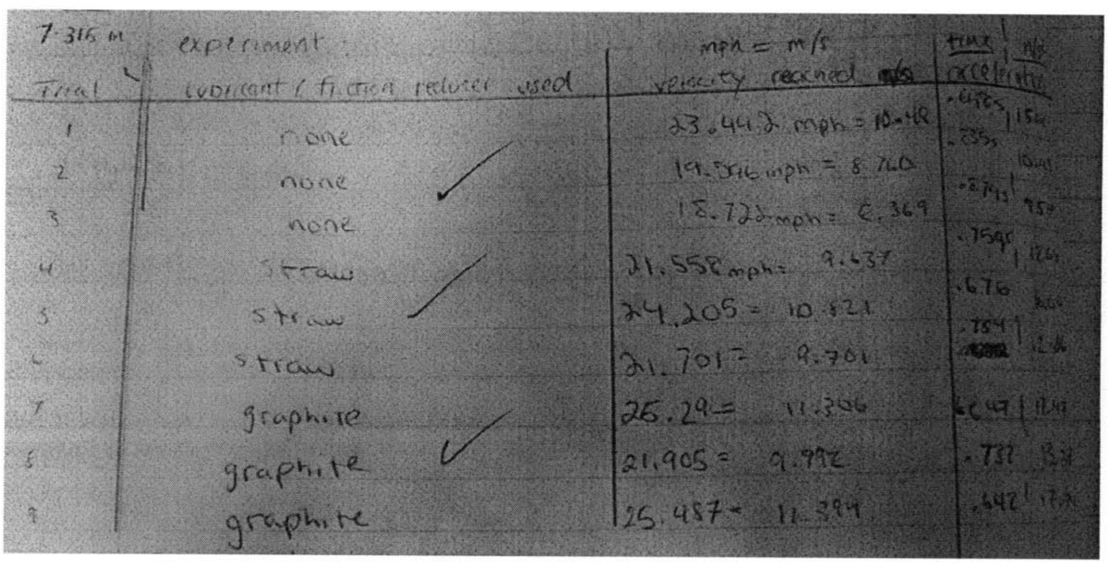


Figure 42: Students learn the value of systematic testing

Some groups began to consider the balance of engineering a complex system as well. If they wanted to drill an extremely deep launch hole to capture large impulse of energy from the compressed gas, they might have to make their car longer, which would increase weight. No groups performed calculations to optimize these multi-variable problems, but they did at least consider it.

The process of manufacturing the car was a platform of lesson-learning for some groups. After many trials of drilling their pressure holes all the way through their car or making the walls so thin that the car shattered when it impacted the end of the track, they began to get a sense for the new set of problems one faces when a part goes from an idealized drawing or design to an actual manufactured item. This point of learning was so profound for one group (presumably because it was the point of most frustration), that they actually made an image of their broken car the cover of their final pamphlet (as seen in Figure 43).

Figure 43: Students learn about the limitations of design and manufacturing

From an engineering perspective though, probably the most important thing they learned was that there is a systematic way to make decisions. The design object for them was to make their car go fast, not to look cool or to pop the biggest wheelie down the track. They really stuck to this objective and were willing to give up the their preconceptions about what they wanted their car to look like in the beginning to design a car based on what best achieved their design objective. Figure 44 shows a group who demonstrated early on their ability to make systematic and effective choices.

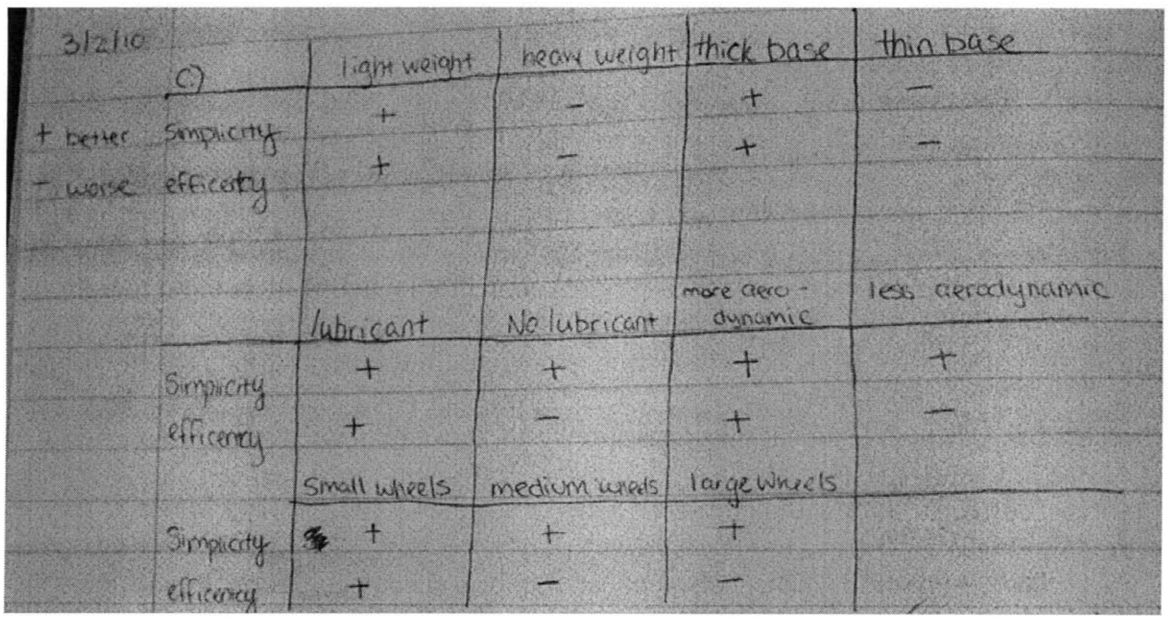


Figure 44: Demonstration of ability to make design-oriented choices

Beyond engineering related experiences, I got lots of feedback from students that working with a group was the hardest part, but that they learned a lot from it. They were formally instructed on the best practices of holding group meetings and understanding their place in group dynamics. It was very impressive to see 9th grade students organizing meetings for 7:00am, taking meeting notes, and assigning accountability for their tasks. Not every group functioned well together, but most groups learned to deal with their struggles constructively. The peer reviews were a huge help in this area because it forced them to take their own accountability as well as the accountability of their peers seriously due to the impact it would have on their grade. Hopefully they will take their experiences from this project, good or bad, and be able to apply the lessons learned to other collaborative situations in later parts of their life. No matter where they end up, they will surely end up using that skill.

VII. Conclusions

1. Did the project succeed?

Any educational research is hard to analyze because there are so many unquantifiable factors to consider. The goal of this project was to see if students could demonstrate a deep ownership of their physics content knowledge by using it to optimize the design of a kit car using an engineering approach. In this regard, the project was a success because many student misconceptions and gaps in knowledge were revealed, and at times, corrected through this project.

The design of the project also appeared to be a success as students appeared motivated and driven to accept and utilize the major components of a systematic design approach. The projected seemed to strengthen the meaning of the scientific approach for students who before this, had not had a good chance to design and run their own experiments. For a good majority of groups, it was also effective in helping them move past major preconceptions about their vehicle design and focus on the instead on making decisions that were best for the system they were working on.

The project seemed to succeed in other intangible ways as well. It was good exposure for the students to see an open ended problem where creativity was needed to get past most hurdles of the project. They learned how to use the rules and design restrictions to their advantage and approach them with a critical mind. In accomplishing these things, students simultaneously learned how to, and in some cases how not to, work effectively in a group project. One final measure of success was the fact that students appeared to be having fun with the project, which is a vital piece to making any learning environment work well. It is unknown exactly how much students learned, especially since most learning isn't realized until weeks, months, or even years after an experience, but it is certain that the project provide value in some shape or form to most students.

VIII. Future of the Compressed Gas Racer Project

1. Lesson learned

In reflecting with the teachers who helped me run the project, we decided that a few things could be changed for the future.

- We never wrote in the rules that the cars actually had to have wheels (and it turns out they went faster without them), so we decided the rules should be that it must use at least 2-3 wheels.
- We agreed that the timing was effective, since no group was allowed to leave the project until the last minute.
- Giving students two weeks instead of one week for the first module is important, since they need time to buy their kits and learn the processes.
- Every year the competition should change slightly. Lots of "trade secrets" got leaked between teams and classes. It is important that every year, students come into the project not knowing the answers. Perhaps a 4-year rotation of project

objectives would be good since students would forget the best way to approach the design problem. As long as the project incorporates the car, the track, and the design process, anything could work. Perhaps the cars could carry a delicate payload, or perhaps the cars might have to stop within a certain distance instead of just going as fast as possible. Those are just a few ideas that could potentially be implemented.

As it stands at the time of writing this, the school that allowed this work to be done with its students is enthusiastic about continuing the project for future classes. There was even interest from the math department to develop a similar project that emphasized the application of calculus and higher-level optimization. I will continue to make myself available as a resource to this school as they move forward with this work.

IX. References

Introduction

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Appendices

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"Brainstorming Tutorial." 2.009 Product Design. Professor David Wallace, 2009. < http://web.mit.edu/2.009/www/schedule/LectureList.html>

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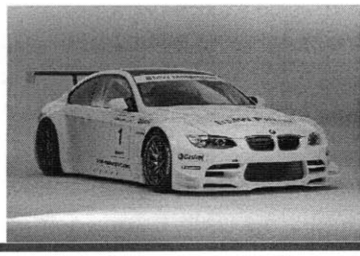
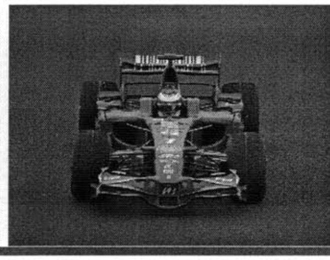
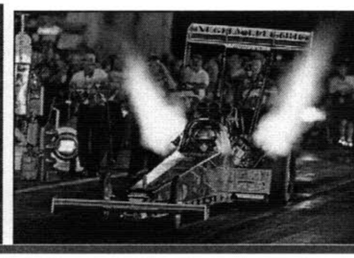
Appendices

Appendix A – Project Syllabus

Compressed Gas Race Car: Project Syllabus

Project Outline:

You will be working in groups of 4 to *design* and build a car that will be optimized to achieve maximum speeds on the Kelvin racetrack set up in Mr. Duggan's room. Each team will be provided with enough parts to construct 3 cars, but you only need to submit one car for the final race. Each group will be given a design notebook where you will keep all of your sketches, calculations, and testing results. This lab notebook will be a substantial part of your grade, so keep it detailed and organized. Remember, this is a physics class, apply what you have learned! The final race will be held on **March 24th, 2010 (Wednesday).** You will record your final car speeds on that day as well as create a brief brochure outlining your design process and final design decisions.

Work Flow:

I will be collecting your design notebooks on a weekly basis. Please see the "How to keep a good design notebook" document posted on The Happy Physics website before you begin your work

Week 1 (Feb. 22nd – March 3rd): Read through the "Preparing to Design" document posted online. Answer the questions at the bottom in your design notebook. Brainstorm 5 different things that could affect the performance of your car and write these down in your notebooks.

Week 2 (March 3rd – March 17th): Design Element #1 - testing, calculations, and conclusions due.

Week 3 (March 17th – March 24th): Design Element #2 - testing, calculations, and conclusions due.

Week 4 (March 24th – March 31st): Design Element #3 - testing, calculations, and conclusions due. Opportunity to consult with Mr. Williams about car-related issues before race.

Week 5 (March 31st): The final race (product brochures due).

What is a "Design Element"?

There are many design aspects that will affect the performance of your car. There are lots of non-conservative forces at work on your car when it is moving. How will you most efficiently harness the energy from the compressed gas driving your car? How does the size and shape of your car affect how fast it will go? Your cars should be hitting the 40-50mph range after modifications. Without effective modifications, your car will only be going around 30 mph at best.

- **You will need to identify at least 3 design aspects to improve on your stock car kit and do some detailed design, analysis, and testing to show that you have optimized that element of design (use the design process as outlined in the "Preparing to Design" document.**
- **In your design notebooks, you must show (using basic physics) how your proposed changes will increase the top speed of your car. <u>You must calculate the speed increase you expect from your modification.</u>**
- **Then you will need to apply your proposed changes to your vehicle design. You must include sketches and dimensions of your changes.**
- **You will then need to design an experiment to experimentally show (using actual track-testing) the results of your modifications. Please include a brief description of how you set up these experiments to isolate the one variable you are testing. <u>Explain why your actual results differed from your calculated results as best you can.</u>**
- **You may change more than 3 things on your car (this is encouraged), but detailed analysis is not required for these changes**

Rules of the Competition:

- There are no size limits on your car, but you must still leave a <u>minimum</u> of a ¼ inch of material around the pressurized gas hole drilled into the back of your car
- To keep things fair, nothing besides lubricants and decorative pieces (including paints) can be purchased on your own to add to the car. You are allowed to get creative about *how* you use the parts given to you in your car kit
- The cars must ride along the guide string with at least two eye-hooks
- The only power source for the car allowed is the compressed gas delivered through the launch-tube
- Cars are judged on speed alone, not reaction time of the user

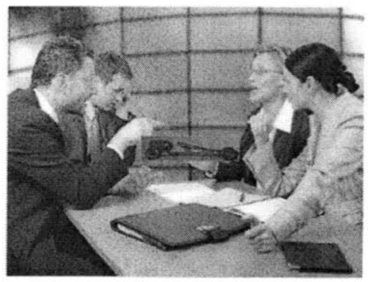
- Anything built must be **safe** to use in the classroom and must follow all over-arching school rules
- Top recorded speed in class gets 10% grade boost (grade boosts affect the entire project grade), winner of all elimination races gets 5%, and best looking car gets 2.5% (decided by class-vote).

Deliverables and Grading Breakdown:

- Design Notebooks (60% total, or 15% per week)
- (Note on lab notebooks: 25% deduction for 1 week late, 100% deduction for 2 weeks late)
- Final Brochure (20%)
- Having a working car for the final race (10%)
- Group Peer Review (10%)
- Grade Boosts for best cars in the class (see above)

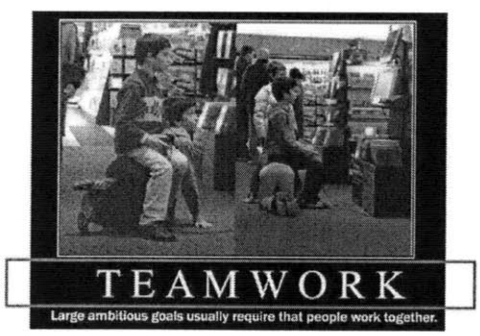
Appendix B – "How to Design" presentation

Preparing to Design



Here are a few tips for how to generate, select, and implement effective ideas as a team

How to Function as a TEAM



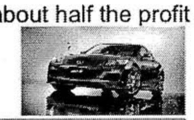
"Don't forget, peer reviews will be 10% of your grade!" -*me*

(*Image from:* http://www.sirhc.info/wp-content/uploads/2009/09/teamwork.jpg)

Why learn how to work well with others?

Exercise: How much would it cost to waste 60 minutes in a company meeting?

- Assume 6 engineers (yearly salary: $80,000) and 2 managers present (yearly salary: $150,000).
- Assuming they all have 20 days of annual leave and work 48.2 hours a week, 60 minutes represents $405 in salary
- Including the opportunity cost of lost productivity, the company technically lost ~$810
- To put that in prospective, that is about half the profit a car company makes on an entire $27,000 car...



Key point: You must learn to be efficient

The keys to holding successful group meetings

Meetings ≠ Hanging-out with friends

- Be on-time and arrive with all of the materials you are responsible for bringing
- Clearly define the goals of the meeting, what milestones are you working to meet?
- Defines roles for individuals (lab-note book keeper, organizer/communications master, construction guru, modeling guru) -Note: that doesn't mean that everybody doesn't help out with every job

2

How to run meetings cont...

- Encourage everybody to contribute
- One conversation at a time
- Challenge IDEAS not individuals (eg. "I think idea A would work better than idea B", not "your idea sucks, lets use mine")
- Be conscious of the fact that you may be dominating the meeting, let others speak
- As a group, don't allow unconstructive negativity
- Always be constructive, use the language of science to communicate ideas (don't be afraid of sounding weird)
- Stay focused on primary goals at-hand

How to wrap-up a meeting

Seeking Closure

- What actions are needed and who is responsible (document this!)
- Recap decisions that were made (make sure these were documented as well)
- What issues still remain unresolved
- When is the next meeting
- Thank each other and end the meeting

3

How To Brainstorm For Success

- Quantity is more important that quality here, just sit down and get as my ideas down on paper as you can. Don't worry if some of them sound a bit silly, they might end up working!
- Use quick sketches or bullet points to communicate ideas
- Never make fun of somebody else's idea, we are trying to generate ideas of *all types*

Example: How could I cut a piece of bread in half?

- Use a knife
- Use a hot wire
- Use a laser
- Use a chain-saw
- Shoot it in half with a pellet gun

The key here is that <u>all</u> of these ideas are *solutions*, we can decide later which one makes the most sense

4

How to select the best idea

- Brainstorming generates lots of ideas, you will need a way to compare them
- Must pick criteria to compare them first (cost, time, complexity, expected performance, uniqueness, etc…)
- Do some quick calculations or research if you can't tell right away what one idea will deliver in a given criteria area
- Choosing with, *"but this one looks way cooler!"* - probably *isn't* the best way to do well in this project

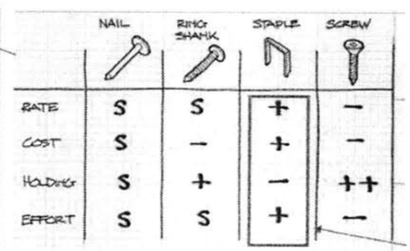
What happens when you aren't thoughtful about the way you choose things?: *Jamarcus Russell* ☹

Example of a good analytical approach to choosing an idea

- Below you can see how different fasteners are compared methodically to a known benchmark, the nail:

Note: S = Same
+ = Better
- = Worse

But you can compare things however you want, as long as it is an objective approach



	NAIL	RING SHANK	STAPLE	SCREW
RATE	S	S	+	–
COST	S	–	+	–
HOLDING	S	+	–	++
EFFORT	S	S	+	–

The staple looks like the best option here, doesn't it?

Image taken from Professor David Wallace of MIT "brainstorming tutorial"

Now that you've chosen a direction: Design & Model

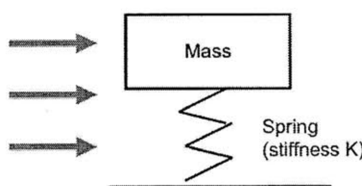
- This is the part where you definitely need to start showing some rough calculations and analysis. Be independent, if you don't know the weight of your block of wood, go to a scale and measure it!
- You may use the internet to do research too, it is useful for finding things like drag coefficients
- Develop small scale experiments of your own if needed to figure things out like coefficients of friction
- Think about how you can optimize your idea within the frameworks of competition rules

Image from: http://www.sps.calpoly.edu/pics/MaytheFma_large.jpg

Remember!

- Calculations are ROUGH, you are allowed to make *good* estimations on some things and simplify the problem to make it solvable.
- But! Make sure your calculations give you meaningful results

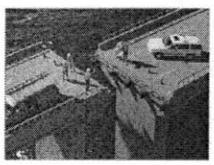
Super complicated suspension system

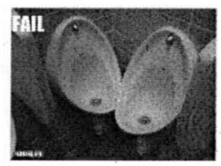


Simple model of suspension that is easy to work with

Before you cut, modify, or make new parts…

- Using the tools available to you, is it physically possible to build it? (for example, could you really drill a hole that gets wider as it gets deeper?)
- Will you be cutting into important parts of your car? Will any parts interfere?
- Use common sense and THINK before you cut!





Now go to the track and test your ideas

- Use actual track-data to see the results of your modifications.
- Are the results not what you thought they'd be? Work as a group to identify problems and trouble-shoot them.
- Don't get frustrated, tuning your car for the final race will take lots of trial and error. The best way to feel confident on race-day is by staying ahead of schedule and doing *lots* of testing.

7

Recap of Design Process

1. Have clear understanding of design objective (making your car go fast)
2. Brainstorm ideas that could achieve objective
3. Select ideas from brainstorming that seem most logical to implement
4. Do analysis on idea and apply it to design
5. Build your idea
6. Test your idea
7. Reflect on results, trouble-shoot, fine-tune or try something else

One More Time…

- **In the frenzy of car testing that will soon ensue, just be sure to record all of your results and revelations in your LAB NOTEBOOK (I'm serious about that)**

LAB NOTEBOOK

LAB NOTEBOOK

LAB NOTEBOOK

Completeness + Organization + Neatness = Good Notebook Grade, Whoa!

8

Questions for your Lab Notebook: **Due March 3rd**

1. Based on the "keys to holding a successful meeting" section, write down the 3 points that you think are the most important to uphold. Briefly explain why you chose these key points.

2. Brainstorming Activity:

   a) to practice brainstorming, get out a timer and see how many ideas you can generate on this topic in 2 minutes: "How could I make Watertown High a more delightful experience?" Is it easier to pick certain sub-areas such as "food" or "teachers" or "building conditions" etc. to help guide your thinking? QUANTITY OVER QUALITY - go wild!

   b) Now set your timer for 5-10 minutes. As a group, brainstorm all of the changes you could possibly make to your car that would get it to go down the race-track faster.

   c) What factors are important to you as a group when choosing which ideas to implement? Look back to the decision-making chart (nails vs. staples etc.) if you need a prompt. List those ideas clearly in your design notebook.

3. Use your brainstorming and design criteria to systematically choose and rank 5 changes you would consider making to your car.

4. Quickly show how you would model the interface between your axle and car body if you were trying to figure out how large the friction force was between the two. Can you come up with an expression for how large this force might be? You are allowed to make up variables for the mass of your car etc.

9

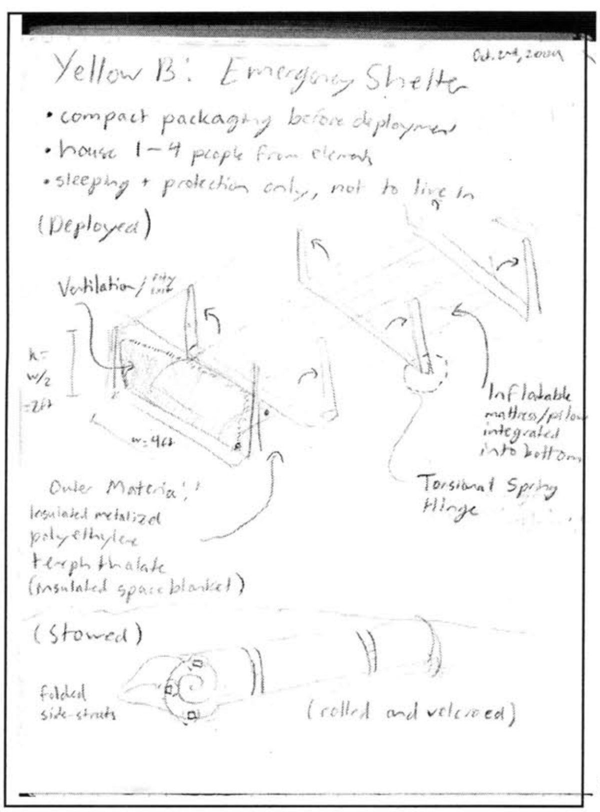
Appendix C – "How to Keep a Design Notebook"

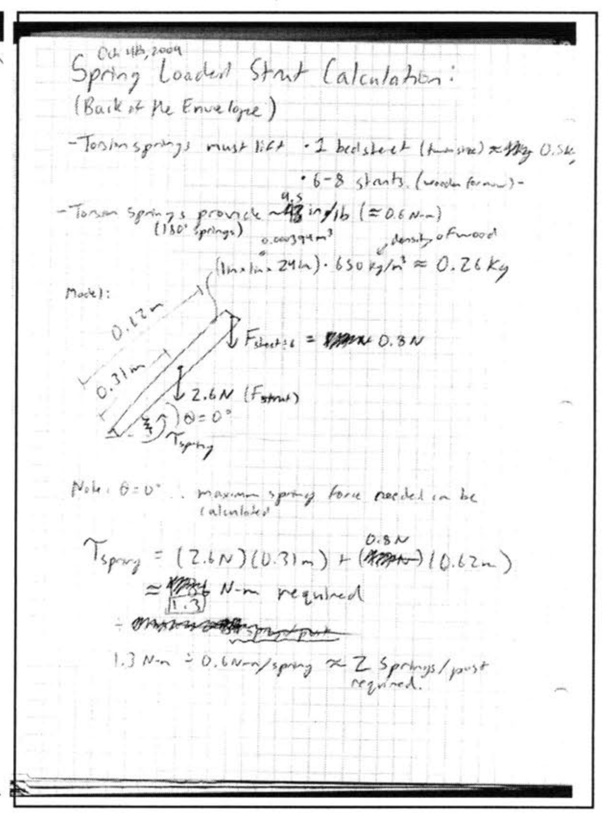
How To Keep a Design Notebook

A design notebook is a working document where you are able to show all of your progress and contributions towards a project. Not only are design notebooks important legal documents (should you ever want file a patent for your work), but also they are an industry standard for most science-focused jobs. You should include all of your brainstorming, thought-processes, analysis, and testing results in an organized and legible manner. Below are a few good practices that you should be following:

- **Date Every Page**
- **Use only pen to write (not pencil)**
- **Neatly cross-out mistakes (it's okay to make them here, this is not a cleaned up final draft of anything, it is a working document)**
- **If you need to attach loose pages, glue them in and date the page**
- **Keep clear diagrams and drawings, include units in calculations**
- **<u>Keep it organized and understandable</u>**

Below is an example of two pages from one of my old design notebooks:





Appendix D – Group Members and Individual Role Form

Class____

Period_______________________________________

Group Members (and team position:
- **Organization / Communications Master**
- **Lab Notebook Keeper**
- **Modeling Guru**
- **Construction Guru)**

_1____

_2____

_3____

_4____

_(5)____

Team Name:

Appendix E – Warning Note to Students

NOTICE

Dear students,

I think it was unclear exactly what I am looking for in your notebooks this week. Since it was the first week, I tried to go a little easy on the grading. Mr. Duggan has uploaded some very specific guidelines to what I'm looking for to give you full credit onto his website. Starting this upcoming week, I will be looking for those specific things and will grade much more strictly based on the inclusion of those elements. Once again, please see Mr. Duggan's website for more details on what I'm looking for. I will try to assign specific point totals to each element if that would help.

Best,

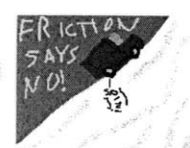
Mr. Williams

Appendix F – Helpful Hints

Some general areas you might want to consider when choosing your *Design Elements*

1

Sources of Friction

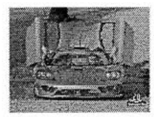


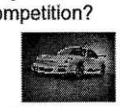
- $F_{friction}=\mu*F_{normal}$
- Any two surfaces moving relative to each other will experience friction forces
- What parts are experiencing relative motion on your car?
- Friction is a non-conservative force, can you calculate the work friction does to oppose your cars motion? How can you relate this to the total energy loss of your car? (and how can energy be related to vehicle speed?)

2

1

Vehicle Weight

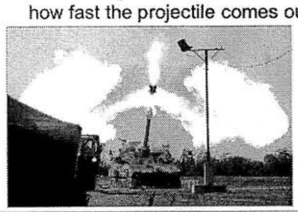
- F=ma…
- $E_{potential} = E_{kinetic} + E_{losses}$ ….
- Why can this ZX-10 motorcycle that weighs 170kg and produces 150hp go from 0-60mph in 3.2 seconds, while this Saleen S7 sports car that weighs 1338kg needs 750hp(!) to also do 0-60mph in 3.2 seconds?
-  vs 
- How important is vehicle weight? Why do they use *hollow* bolts in the ZX10? Why did Porsche replace the door-handles on their new 911 GT3-rs with strips of fabric?
- Is there a limit to how much you can reduce/add mass without breaking the rules of the competition?


3

Harnessing Potential Energy From Compressed Gas

- How does the energy stored in the compressed air relate to the kinetic energy of your car?
- Does all of the gas get released instantly? How does this relate to the concept of impulse (I = F*t)? Do you want to maximize or minimize the impulse on your car from the compressed gas? How would you do this without altering the amount of force the compressed air exerts on your car?
- Do the lengths of the barrels on the tanks shown below affect how fast the projectile comes out?




4

Perfecting Launch Conditions

- Without changing your car, can you affect its top speed by adjusting how you set your car up on the track or by ensuring the compressed air is at a certain psi level?
- The interface between the launch tube and your car is very important, what can you change about the way this is set up before a race?
- Do you notice that any other set-up factors affect your car performance on a given run?

7

Good Luck!

8

4

Appendix G – Student Peer Review Form

Name:

Period:

Group:

Peer Reviews

Please list each group member below and give them a score between 0 and 100 based on their overall performance with your group. Did they show up to all meetings on time? Were they prepared? Did they fulfill their duties as notebook managers, fabrication gurus etc.? Were they always constructive with their input? Did they contribute evenly to the workload of the project? Think about these things as well as any other factors you felt were important to the successful completion of your project:

For each group member, please give feedback in the following areas. They will receive an anonymous compilation of this feedback, so be constructive. Clearly indicate the question (1-3) that you are answering for each peer:

In future collaborative projects, this peer could…
1) keep doing…
2) do more of…
3) do less off…