What Can You Learn About Systems Engineering By Building a Lego™ Car?

INCOSE IS 2018

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Los Alamos National Laboratory (LANL) has experienced underutilization of mid-career female R&D Engineers over many years.

- *Underutilization* exists when the representation of female and minority incumbents in a particular job group is less than 80% of availability
- We are making progress through
  - Targeted recruiting
  - Pipeline programs

The Future Female Leaders in Engineering (FFLIE) program is a pipeline strategy that helps LANL meet its affirmative action goals.

The FFLIE program design leverages recent literature on variables affecting women's success in engineering.

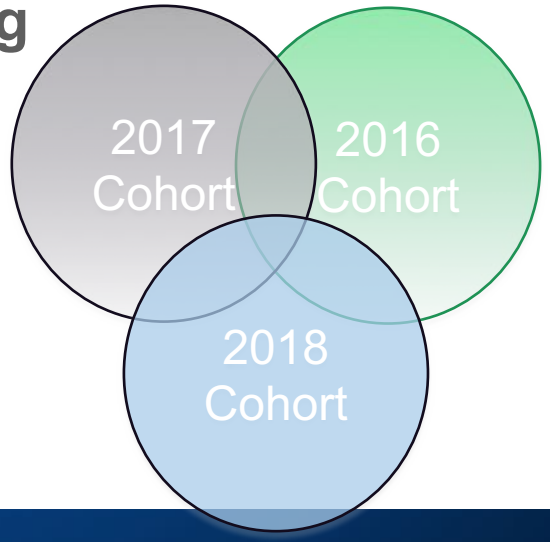
- Three main program elements:
  - Technical work assignment
    - Minimum of two eight-week summer internships in a LANL R&D organization
  - Professional enrichment activities during the summer internships
  - Graduate education through a MS
- Intent is that graduates come back to LANL to start their careers as Female Leaders in Engineering

Work assignments are crafted to challenge the student and help her develop and strengthen new technical skills.

- LANL's broad mission space affords opportunities to match nearly any student's interests with an organizational need
- Each LANL student has a work plan that sets out clear responsibilities, goals, and success paths
- Technical hosts are encouraged to assign a female technical mentor, where possible, and to expose the student to as many female engineers as are available in their organization

Professional enrichment activities are delivered in a cohort format to help students develop their social network.

- Professional enrichment activities are intended to develop skills that will enable participants to successfully apply their technical capabilities in the LANL work environment
- Professional development is delivered by four female professional development mentors, three of whom are engineers
- Program includes networking opportunities with female engineers from various professional backgrounds as well as near-peer mentoring and networking



Professional development activities focus on skills that enable successful application of students' technical capabilities in the LANL work environment.

- First year enrichment activities revolve around the LANL R&D Engineering Primer
  - Navigating the R&D Engineering Enterprise @ LANL
  - Mission Assurance Framework
    - Integrated application of systems engineering (SE), project management (PM), and engineering quality and rigor (QA)
    - Focus is on activities and artifacts more than theory
    - Includes hands-on practice on a demonstration project
  - Technical writing and presentation skills
- Second year enrichment activities involve a Design Thinking project and ongoing honing of technical writing and presentation skills

- Professional development activities "equip the women."

Key Artifacts for the Project and SE Lifecycles

Initiating	Planning	Executing	Closing
Monitoring & Control			
• **Statement of need** • **High level problem definition** • **Stakeholder list** • Statement of Work (SOW) • Summary budget • Summary milestone chart • Risk level determination • Approval, review, documentation, Configuration Management (CM) level requirements	• **Functional & performance requirements** • **Support requirements** • Preliminary technical baseline • **MOP & V&V plans** • Project team identified • Cost & schedule baselines • Work Breakdown Structure (WBS) • Risk register • Project/product scope statement • Change & CM plans • Key management review plans	• Function analysis & allocation • Architecture design • **Prototypes** • **Trade studies** • Manage, monitor, & control project work, scope, schedule, costs, human resources, communications, risks, & stakeholder engagement • Execute change control and Configuration Management • Execute key management reviews • System integration • V&V	• Transition to operations and maintenance • Customer acceptance testing • Document customer acceptance • Conduct post-project reviews • **Document lessons learned** • Disposition organizational assets • Contract/Financial system closeout • Procurement closure • Final management review

MOP = Measures of Performance
V&V = Verification and Validation
Blue = Systems Engineering;
Green = Project Management;
Gray = Quality
Bold = Covered in training

Conceive	Design	Implement	Operate	Retire

Lego™ Derby Race Scenario

You just showed this flyer to your teammates and you have decided to build a car as a team and enter the derby. Your car must not only win the race, but your design must also wow the judges!

MiniBrick Derby
Where: Bradbury Science Museum
When: August 2
Enter Today!

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Rules

Derby Car Dimensions
The overall length of the car shall not exceed 7 inches.
The overall width of the car shall not exceed 3 inches.
The car shall use standard Lego™ blocks and LegoDerby wheels and axles.
The car shall have 3/8" clearance underneath the body so it does not rub on the track.

Derby Car Weight
The car shall not exceed 5.0 ounces.
The official race scale that is used at car check-in shall be considered final.

Wheels and Axles
The wheels shall not be cut, drilled, beveled, or rounded. Seams and imperfections may be removed from the wheels The axles may be altered, polished and lubricated.

Car Modifications Not Allowed
Wheel bearings, washers or bushings are prohibited.
The car shall not ride on any type of springs.
No starting devices. The car shall be freewheeling.
No loose material of any kind, such as lead shot, shall be used.

Other Race Rules
Once a car passes inspection and is entered into the race, only race committee members can touch it.
If the car loses a piece, or is otherwise damaged, the racer shall have 5 minutes to make a repair.
Each car must pass inspection by the official inspection committee before it will be allowed to compete.
The Inspection Committee has the responsibility to disqualify those cars that do not meet these specifications.

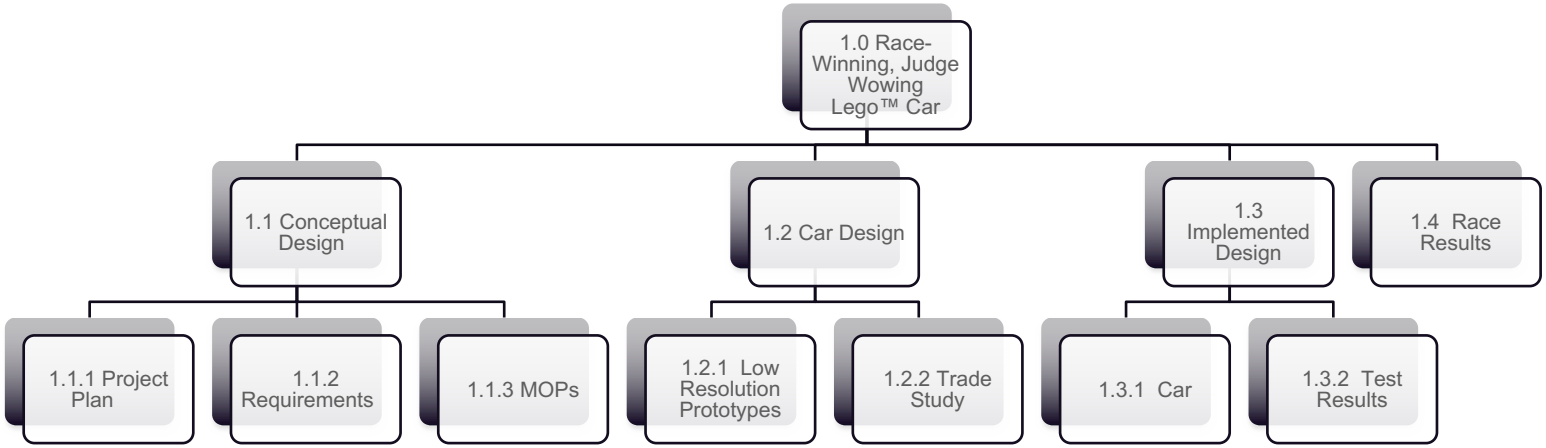
Additional Project Information

- Your team has a limited budget, and must spend no more than $200 on materials for this project
- There are general purpose tools and equipment available for your use that don't count against the cost of the project
- If you want any specialized tools or equipment, you will have to buy them from the Derby Store

Exercise – Planning and Scheduling

- **Develop a task list and schedule for your project**
  - Remember what you've learned so far about project initiation and planning artifacts
  - Must include performing trade studies (evaluating design options – more on that later!)
- **Address the following:**
  - What tasks must be done?
  - Who's going to do them?
  - Are there tasks that must be completed before other tasks can start or can be completed?
  - When can each task start and how long will it take to complete?

Sample WBS and Project Schedule for the Lego™ Car Project



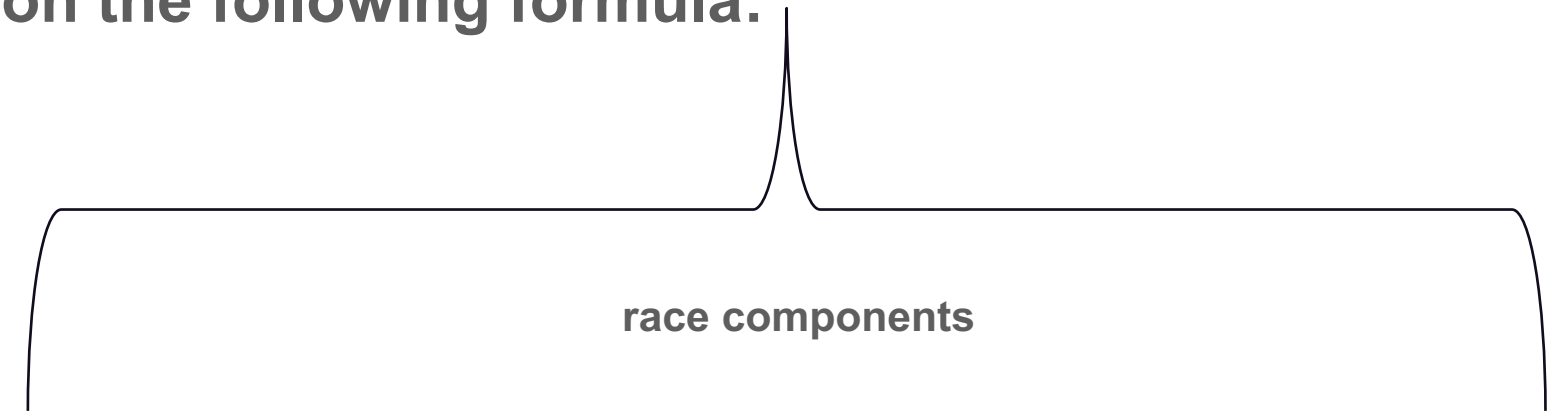
	Wk1	Wk2	Wk3
1.1.1 Project Plan	3 hrs		
1.1.2 Requirements	5 hrs		
1.1.3 MOPs	4 hrs		
1.2.1 Low Resolution Prototypes		3 hrs	
1.2.2 Trade Studies		4 hrs	
1.3.1 Realized Car			4 hrs
1.3.2 Test Results			6 hrs
1.4 Race Results			1 hr

Practice – Requirements

- Using the info from the Derby flyer and anything else you've learned so far develop the following:
  - Statement of need
  - Stakeholder list
  - Constraints
  - Functional, performance, and support requirements
  - Measure(s) of Performance (MOPs) for each requirement
- Hints:
  - Requirements shall be arranged hierarchically and shall be traceable to the statement of need
  - MOPs should be things that can be verified in different ways as the project progresses

Practice – Requirements

- You realize that you don't know what "Win the race means" so you contact the race officials and ask them
- They tell you that the competition will be judged based on the following formula:



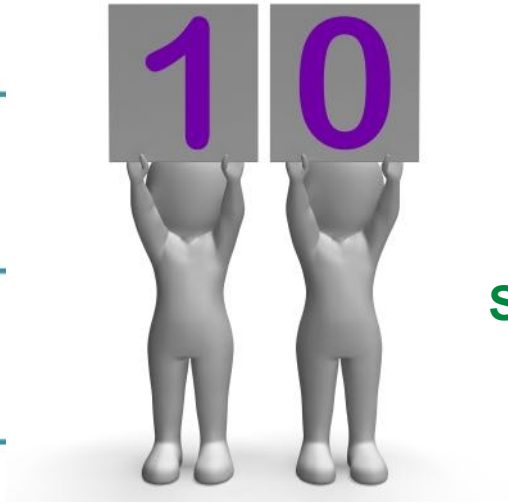
Overall Score = .6(1/Time to Fixed Point) + .2(Distance) + .2(Wow Factor)

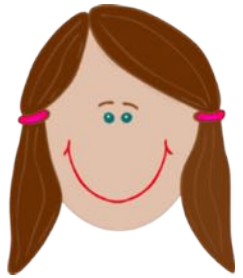
Results – Requirements

Representative statement of need:

The project shall provide a race-winning Lego car that wows the judges, conforms to all derby rules, and is able to be repaired by the racer, by August 2, 2017

Students identified the following stakeholders:





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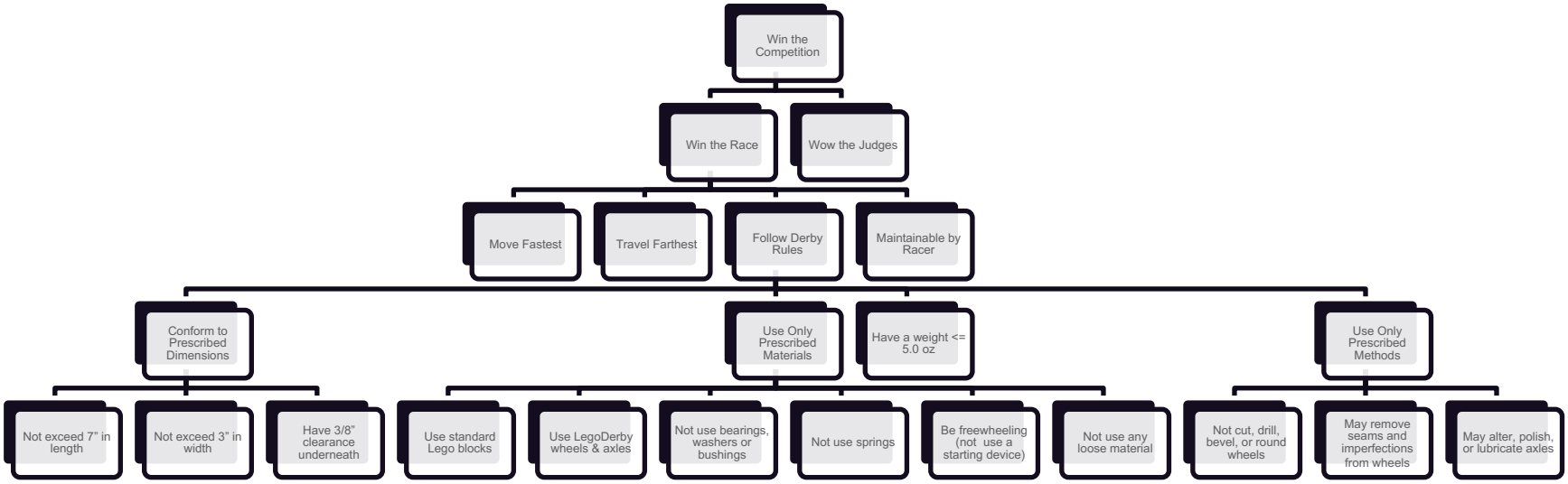
Images from freedigitalphotos.net/

Results – Requirements

- Students identified the following constraints:
  - Cost
    - Project cost shall not exceed $200
  - Schedule
    - Derby car shall be built in time to compete in a 8/2 race
- There was an additional constraint associated with materials:
  - Derby car shall be built only from the materials on the materials list

Debrief – Requirements

The car shall



Results – Requirements with Measures of Performance

1.0 The car shall win the competition

1.1 The car shall win the race

1.1.3 The car shall follow Derby Rules

1.1.3.1 The car shall conform to prescribed dimensions

MOP: All child requirements are satisfied (by analysis)

1.1.3.1.1 The car shall not exceed 7” in length

MOP: The measured car length (by test)

1.1.3.1.2 The car shall not exceed 3” in width

MOP: The measured car width (by test)

1.1.3.1.3 The car shall have 3/8” clearance underneath

MOP: The measured car ground clearance (by test)

Results – Requirements with Measures of Performance

1.0 The car shall win the competition

1.1 The car shall win the race

1.1.1 The car shall move fastest

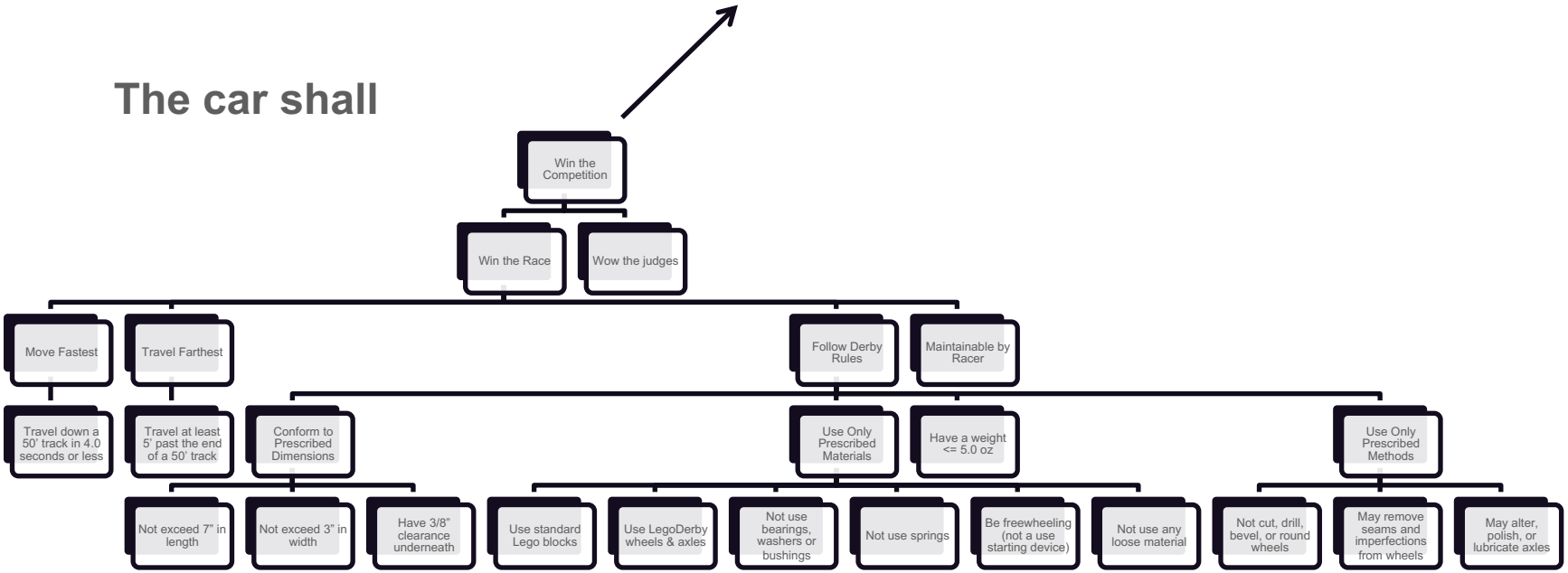
MOP: ? How fast must the car be able to move?

1.1.2 The car shall travel farthest

MOP: ? How far must the car be able to travel?

Results – Requirements

Overall Score = .6(1/Time to a Fixed Point) + .2(Distance) + .2(Wow Factor)



Debrief – Requirements with Measures of Performance

1.0 The car shall win the competition

1.1 The car shall win the race

1.1.1 The car shall move fast

MOP: The car passes the speed test at least 90% of the time, over a minimum of 10 test runs (by test, analysis)

1.1.1.1 The car shall travel down a 50’ track in 4.0 seconds or less

MOP: The time it takes for the car to travel down the track (by test)

1.1.2 The car shall travel far

MOP: The car passes the distance test at least 70% of the time, over a minimum of 10 test runs (by test, analysis)

1.1.2.1 The car shall travel at least 5’ past the end of a 50’ track

MOP: The distance the car travels past the end of the track (by test)

Debrief – Requirements with MOPs Become the Test Plan

Requirement ID	Requirement -- Unless stated other wise, each begins with "The car shall	MOP	Method	Test Result
1	Win the competition	All child requirements are satisfied	Analysis	1.1 verified 1.2 verified…
1.1	Win the race	All child requirements are satisfied	Analysis	1.1.1 verified 1.1.2 verified…
1.1.1	Move fast	The car passes the speed test at least 90% of the time, over a minimum of 10 test runs	Test, analysis	x of y tests passed
1.1.1.1	Travel down a 50' track in 4.0 seconds or less	The time it takes for the car to travel down the track	Test	Test 1: a sec Test 2: b sec…
1.1.2	Travel far	The car passes the distance test at least 70% of the time, over a minimum of 10 test runs	Test, analysis	x of y tests passed
1.1.2.1	Travel at least 5' past the end of a 50' track	The distance the car travels past the end of the track	Test	Test 1: a ft Test 2: b ft…
1.1.3	Follow Derby Rules	All child requirements are satisfied	Analysis	1.1.3.1 verified 1.1.3.2 verified…
1.1.3.1	Conform to prescribed dimensions	All child requirements are satisfied	Analysis	1.1.3.1.1 verified 1.1.3.1.2 verified 1.1.3.1.3 verified…
1.1.3.1.1	Not exceed 7" in length	The car length specified in a scale drawing	Inspection	Specified length:
		The measured car length	Test	Length:
1.1.3.1.2	Not exceed 3" in width	The car width specified in a scale drawing	Inspection	Specified width:
		The measured car width	Test	Width:
1.1.3.1.3	Have 3/8" clearance underneath	The car ground clearance specified in a scale drawing	Inspection	Specified clearance:
		The measured car ground clearance	Test	Clearance:

Practice – Trade Studies

Use trade studies to make all major design decisions!

- Conduct a trade study to down-select to a final wheel design
  - Performance given standard wheels vs weighted wheels

Image courtesy of clipartfest.com

Results – Trade Studies

Goal: Make a decision about what type of wheel will yield the best performance.

Variables of interest:

- Contribution of the wheels to overall vehicle weight
- Weight distribution
- Friction

Additional variables considered:

- Wheel size
- Wheel spacing
- Cost

Weights:

- Weight distribution .5 (contributes to both speed and momentum)
- Friction .4
- Overall vehicle weight: .1

Debrief – Trade Studies

Wheel Configuration	Weight Distribution	Weighting Factor	Friction	Weighting Factor	Contribution to Overall Vehicle Weight	Weighting Factor	Total
3.6 oz set	2	0.5	1	0.4	6	0.1	2.0
1.8 oz rear, standard front	6	0.5	4	0.4	3	0.1	4.9
1.8 oz rear, 1.1 oz front	4	0.5	2	0.4	5	0.1	3.6
2.2 oz set	2	0.5	3	0.4	4	0.1	2.6
1.1 oz rear, standard front	5	0.5	5	0.4	2	0.1	4.7
standard set	2	0.5	6	0.4	1	0.1	3.5

- 1.8 oz rear, standard front wheel is the winner, but 1.1 oz rear, standard front wheel is a second alternative
- Weighting factors matter – the two weighted rear, standard front options tie (4.7) if the weightings for friction and weight distribution are flipped

Results -- Prototyping

Practice – Implement

- **Build and test the Lego™ car per the specifications resulting from your trade studies**
  - –Will need to develop requirements and MOPs for design quality and aesthetics if this hasn't been done yet
- **Record test results**
- **Iterate design as necessary to improve performance against requirements**

Practice – Deployment (Show time!)

- **Each student will give an oral presentation on her trade study**
- **Each car will be inspected for conformance with Derby rules**
  - –Disqualified cars will not participate in the race
- **Each team will have one run of their Lego™ car**
- **Expert panel will judge design quality and aesthetics**
- **Awards**
  - Hare – the fastest car
  - Camel – the car that goes the longest distance
  - Unicorn – the most pleasing car
  - Princess – the car with the highest combined score

So, What Did the Students Learn About Systems Engineering?

About requirements and MOPs:

- How to distinguish between a requirement and a constraint; how difficult it is to write a good requirements set
- The proper uses of “shall” and “may” in requirements writing
- That the inability to define MOPs is an indicator of a poorly specified requirement

About design, specifically trade studies and prototyping:

- Trade studies don’t have to be scary!
- The weighting factors matter
  - Need to carefully consider how the variables interact with the most important design requirements
- Applying Newton’s Laws in engineering design
- The value of keeping configuration management on prototype evolutions

About verification and validation:

- The need to ensure that measurements accurately reflect the characteristic of interest
- The sometimes critical importance of meeting stakeholder needs to overall project acceptance
- How to use MOPs on qualitative criteria for verification

What Else Did the Students Learn About Systems Engineering?

In addition to the technical competencies, the Lego™ project provided exposure to:

- Core principles: systems fundamentals and system lifecycle
- Professional competencies: team dynamics and negotiation skills
- Technical management competencies: planning and configuration management
- Cross-discipline understanding of project management

(See Gelosh et. al., 2017, for a description of the INCOSE Competency Framework.)

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