NZ Engineering Science Competition Judges Report 2022

The fourteenth annual "NZ Engineering Science Competition" was held from 10am to 6pm on Saturday 6 August 2022. We had 179 teams take part with entries from 61 schools across New Zealand.

Competition Question

"What's the largest payload that could be launched into orbit by slingshot?"

Launching material into space is expensive and the current approach of using rockets consumes a huge amount of fuel. For example, the recent Artemis mission to the moon required in excess of 2 million litres of fuel and even the relatively small Electon rocket uses on the order of 10,000 litres of fuel for every launch. With an increasing number of satellites being launched, it is desirable to come up with a launch mechanism that is both more cost effective and more environmentally friendly, reducing the amount of rocket fuel required.

Various alternatives to rockets have been proposed over the years[1] (and in some instances proof-of-concepts tests have even been carried out). SpinLaunch[2] is in the process of developing a launch system that uses a "slingshot" method as it's primary means of getting into orbit. Their approach having the potential to dramatically reduce the amount of fuel required. The SpinLaunch system is based on the idea of gradually accelerating a launch vehicle to very high speeds by spinning it around faster and faster (in a vacuum), and then releasing it upwards, in the same manner that a slingshot can be used to release a projectile. This is a promising approach but faces some significant challenges in scaling up from the test system that has been built to the full size system[3]. It should also be noted that this approach still relies on using fuel for the final stage of moving into orbit.

The concept of launching a projectile with a slingshot dates back to antiquity (e.g. the biblical story of David and Goliath features the use of a slingshot). Note that these older style slingshots were designed to be whirled around and then the projectile released[4]. This differs significantly in style from the more modern conception of a Y shaped stick with a rubber band, (popularised by games such as Angry Birds), where the projectile is propelled by pulling back on the rubber band and releasing it[5].

The question was deliberately open-ended, with no single "correct" answer, and allowed for a wide variety of approaches to answering it. Teams were expected to research and understand the topic, make appropriate assumptions and then devise a mathematical modelling approach to answering the question, and then write a clear and concise report to present their findings. All of this within just an eight hour period!

A wide range of modelling approaches were taken, and the judges had a difficult task to decide on the finalists and competition winner.

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[1] https://en.wikipedia.org/wiki/Non-rocket_spacelaunch
[2] https://www.spinlaunch.com/
[3] https://bigthink.com/starts-with-a-bang/physics-spinlaunch/

[4] https://en.wikipedia.org/wiki/Sling_(weapon)
[5] https://en.wikipedia.org/wiki/Slingshot

Judging Process

Judging was done over three rounds by members of the Department of Engineering Science and the Auckland Bioengineering Institute. Rounds one and two narrowed the 179 entires down to a shortlist of 13 to enter the third and final round. A panel of three expert judges, with extensive experience in teaching mathematical modelling then reached a consensus on the winning team and the two runner up teams. All judging was completed blind, with team identities only revealed after all judging was completed.

Judge's Comments

Each team needed to first research the topic and write the introduction for their report. Mankind has been launching things into orbit for well over half a century so there is a wealth of information available regarding orbital mechanics. During the research phase, teams who did a good job would likely have come across some key ideas (e.g. to reach orbit, it isn't enough to go straight up, you also need to develop some horizontal velocity so that you can move into orbit). Good researchers would have also encountered some values that were highly relevant to their modelling (e.g. figures for how fast a satellite needs to travel to stay in orbit at a particular altitude).

As part of determining their approach to answering the question, teams needed to carefully consider the wording of the question and in particular what might be meant by "into orbit" and "slingshot". Teams generally interpreted "into orbit" as meaning orbiting the earth and then settled on an appropriate orital altitude of their choice. The question did not specify what kind of orbit so it was fine to interpret this as a Low Earth Orbit (LEO), Medium Earth Orbit or High Earth Orbit (HEO). LEO was a common choice.

Many teams found information regarding SpinLaunch but then a surprising number ignored this information in favour of using an "Angry birds" style slingshot approach. While the question is open to interpretation it is always important when modelling to think about the assumptions made and determine how realistic they are. Using an "Angry birds" style slingshot to launch material into orbit is unfortunately not an approach that is viable. While taking this approach did not exclude teams from potentially placing, a small amount of thought should have allowed you to flag this approach as fraught with peril and unrealistic. Certainly some of the conclusions based by taking this approach should have set some alarm bells ringing.

While making assumptions is vital for reducing the complexity of the problem, many teams made assumptions with little justification or thought as to how realistic that assumption was.

Some common assumptions made were

- Gravitational acceleration is a constant 9.81 m/s^2
- The drag force due to air resistance can be ignored
- To move into orbit just requires reaching an orbital altitude with zero vertical velocity
- The projectile travels in a straight line

The above assumptions certainly simplify things but are all flawed (to various degrees) and will result in an incorrect solution.

For example, the gravitational acceleration is not constant, rather it decreases the further you travel from the surface of the earth.

We can find the gravitational acceleration using $g = \frac{GM}{r^2}$ where;

$G = 6.674 \times 10^{-11}\ \frac{m^3}{kgs^2}$ is the universal gravitational constant,

$M = 5.972 \times 10^{24} kg$ is the mass of the earth, and

r is the distance of an object from the centre of the earth (the earth's radius plus the orbital altitude)

The radius of the earth is approximately 6,371km (i.e. 6,371,000m).

For a very low orbit (e.g. an altitude of 160km) g is reduced but still of similar magnitude:

$$g = \frac{GM}{r^2} = \frac{6.674 \times 10^{-11} \times 5.972 \times 10^{24}}{(6{,}371{,}000 + 160{,}000)^2} \approx 9.34 m/s^2$$

If you had opted for a geosynchronous orbit (which has an altitude of 35,786km) it makes a massive difference:

$$g = \frac{GM}{r^2} = \frac{6.674 \times 10^{-11} \times 5.972 \times 10^{24}}{(6{,}371{,}000 + 35{,}786{,}000)^2} \approx 0.22 m/s^2$$

Assuming a constant acceleration due to gravity when travelling all the way up to geosynchronous orbit is clearly an incorrect assumption.

Likewise assuming that the drag force due to air resistance can be ignored was a poor assumption, particularly as the drag force depends on both the square of the velocity and the density of the air. A slingshot approach necessitates the projectile moving extremely fast at the moment of leaving the ground, meaning it is travelling at a very high velocity through the relatively dense air on the surface of the planet (by contrast a rocket accelerates from rest and doesn't obtain really high velocities until the air is much thinner). Many of the velocities proposed would literally rip the projectile apart or burn it up, due to the drag force (think about what happens to meteorites entering the earth's atmosphere – most of them burn up).

A common model for drag that some teams used is $f_d = \frac{1}{2} c \rho A v^2$ where c is a drag coefficient that depends on the shape of the object (e.g. for a cone c=0.5 whereas for a very streamlined body c=0.04). ρ is the density of the air (roughly 1.2kg/m^3 at sea level) and A is the cross-sectional area of the object moving through the air (e.g. on the order of one square metre for a small projectile such as might be launched by SpinLaunch). To stay in an orbit at an altitude of 200km above the earth requires moving at nearly 8000m/s. To reach this tangential velocity will require launching at a far greater velocity, to counteract the force due to gravity. Even plugging 8000m/s into the above drag model and using a very streamlined body for the projectile shape yields a force at sea level of

$$f_d = \frac{1}{2} \times 0.04 \times 1.2\ \times\ 1\ (8000)^2 = 1{,}536{,}000 N$$

When your drag force is in excess of one and half million Newtons, neglecting it is unwise!

(For contrast purposes, the force due to gravity on a 750kg projectile near the earth's surface is roughly two hundred times smaller than that).

A common mistake was to assume that to reach orbit all that was required was reaching an orbital altitude with zero vertical velocity. Unfortunately if sufficient horizontal velocity isn't imparted, the projectile won't enter orbit, it will just fall back down to earth. Entering orbit requires reaching the required altitude AND having sufficient tangential velocity so that rather than falling back down you fall “around” the earth, entering orbit.

Many teams modelled the motion entirely in one dimension, assuming everything would happen in a straight line. Unless you throw something straight up this is not the case (and as explained above, you can’t launch something vertically straight up and expect it to stay in orbit – it will just come back down again).

Although not necessary to be considered a top entry, a number of teams wrote computer code to support their mathematical modelling. Using numerical computation is a viable approach and can be an excellent technique when faced with equations that are too difficult to solve by hand. It is important to note that any computer code written must add value to the mathematical modelling, rather than just being included to try and impress the judges.

Once a team had found their answer to the question, they then needed to complete their report. A well written report is essential for doing well in this competition. The report should begin with a short summary/abstract that summarises the findings and includes the answer to the question (counter-intuitively, this is often written last). The report should then continue with an introduction, with information that outlines relevant background information and prior research on the topic.

Some teams wrote out separate sections for their definitions and modelling assumptions. While this is not an issue per se, the more common approach in scientific research is to write a dedicated section that describes the modelling approach, which will include the assumptions made and any relevant definitions.

The modelling section was the weakest part of most team reports. The judges found that it was difficult to easily understand or follow the modelling approach taken by many teams. It is important to define any equations or modelling techniques used, preferably with relevant references to other research. Make sure all variables in any equations are defined, so that the reader can understand what is being calculated (see the gravitational acceleration calculations included in this report for an example). Be sure to include units on any results you provided. Including **labelled** diagrams can be hugely helpful here. Your modelling section should be written in a way that is clear and easy to follow by an audience with a similar level of knowledge to you.

The next section should detail the modelling results. Relevant figures and tables can be extremely helpful for assisting readers with visualising the understanding your results. Again **labels** on any graphs are critical. A graph that doesn’t contain labelled axes is very hard for a reader to correctly interpret.

Finally, the report should present your conclusions based on the modelling results.

A key part of the modelling process is reflecting on whether the results obtained make sense, when compared with reality. A few teams did this very well and also pinpointed areas where their model could be improved to better reflect reality. Other teams obtained highly implausible results from their model and didn’t stop to question them. Highly implausible results can indicate errors in your calculations or a model that was based on incorrect assumptions (e.g. perhaps an important factor was not included in your model).

Answers varied hugely, ranging from a few grams to several order of magnitude larger than the mass of the earth (that result should have set alarm bells ringing!) Some teams even concluded that it was impossible to launch anything into orbit via slingshot (this is a perfectly valid conclusion and could in fact be the correct answer, given that even SpinLaunch is anticipating using some fuel for manoevuring their projectile into orbit).

This year’s question was a tough one and perhaps unsurprisingly no single team manged to nail everything the judges were looking for. We recognize it is unrealistic to expect a perfect model to be developed in the short time provided, so it is impressive that many teams made credible efforts, showing excellent modelling skills and creative thinking, communicated in an understandable manner.

How to do better

For those students who will be competing again in the future here are a few tips on how to improve your chances of winning

- Ensure you begin your report with a summary/abstract that briefly describes your approach AND the solution you obtained. Make sure your answer is *clearly* stated in your summary (with units if appropriate).
- Choose your assumptions carefully. Ask yourself "is this a realistic assumption to make?"
- Take care to use a model appropriate to the problem and be aware of your model's limitations (some very sophisticated approaches were unfortunately not applicable to the contexts to which they were applied).
- Explain your approach clearly, so that an audience with a similar level of knowledge can follow your modelling and also understand WHY you have used that approach (some equations seemed to appear out of thin air, with no justification of where they came from or what the variables represented).
- Be sure to show HOW you solved your model (sometimes solutions were presented with no working, we need to be able to follow how you arrived at your answer).
- Use visual tools such as graphs, images,diagrams, figures and tables, where appropriate, to effectively and efficiently present information.
- Make sure you perform a reality check on any solutions obtained. Does the answer seem plausible? Your report should include a discussion of how realistic (or not) your solution is, ideally with reference to existing data. If your model produced an unrealistic answer be sure to discuss why this might be the case.

Results

Winners of The Pullan Prize for first place ($1000 for each team member)

- Team 1185 from Papatoetoe High School, Auckland (Year 13): Fergus Lee, Amanpreet Saini, Deago Tataurangi, Armaan Chopra

Runners Up ($500 for each team member)

- Team 1049 from St Peter's School, Cambridge (Year 12/13): Madi Judkins, Esme MacGillivray, Rebecca Foley, Sarah Ellis
- Team 1187 From Takapuna Grammar School, Auckland (Year 12): Elise Clark, Hariette Johnson, Esther Carr, Joe McKibbin

Highly Commended

- Team 1152 from Burnside High School, Christchurch (Year 12): Johnny Lawrey, Ameya Raut, Olivia Wang,
- Team 1028 from Kristin School, Auckland (Year 12/13): James Xu, Angelina Youssef, Michael Feng, Selina Ren
- Team 1039 from Kristin School, Auckland (Year 13): Tony Lee, Tomas Barrero Ortiz, Alan Qin, Asher Goddard
- Team 1090 from Mount Albert Grammar School, Auckland (Year 13): Alan Li, Arnav Bhatiani, Yujia Karen Zheng, Deboprana Mallick
- Team 1142 from Rangitoto College, Auckland (Year 12): Paco Poon, Sanada Norrington, Jonathan Hii, David Paas
- Team 1008 from St Andrew's College, Christchurch (Year 13): Luke Zhu, Tom Edwards, Toby Harvie, Corin Simcock
- Team 1096 from Takapuna Grammar School, Auckland (Year 12): Ankia Van Zyl, Phyllis Lan, Hyerim Park, Neve Mann Benn
- Team 1150 from Western Springs College, Auckland (Year 12/13): Minh Anh Tran, Arthur O'callahan, Arushi Gupta, Sophia Collins

Participation

We had 179 teams from 61 schools participate this year.

We had many “Action shot” photos submitted during the course of the day. These photos were uploaded to our department facebook page and can be viewed at: www.facebook.com/engsci

Rangitoto College had the most entries from an individual schools with an impressive 14 teams competing. See below for a complete list of schools and how many teams they entered.

ACG Parnell	4	Otahuhu College	3
ACG Strathallan College	4	Pakuranga College	1
ACG Sunderland	5	Palmerston North Girls High School	3
Auckland Grammar School	8	Papatoetoe High School	1
Avondale College	7	Pinehurst School	2
Botany Downs Secondary College	4	Rangitoto College	14
Burnside High School	2	Riccarton High School	2
Christ's College	3	Rosmini College	1
Crimson Global Academy	1	Rototuna Senior High	1
Epsom Girls Grammar School	7	Sacred Heart College	1
Glendowie College	2	Saint Kentigern College	3
Howick College	1	Samuel Marsden Collegiate School	3
Kaitaia College	1	Sancta Maria College	1
Karamea Area School	1	Scots College	1
King's College	7	Selwyn College	2
King's High School Dunedin	1	St Andrew's College	1
Kristin School	7	St Cuthbert's College	5
Liston College	3	St Dominic's Catholic College	2
Logan Park High School	1	St Paul's Collegiate, Hamilton	1
Lynfield College	5	St Peter's School Cambridge	2
Macleans college	9	Takapuna Grammar School	7
Massey High School	2	Tauranga Girls' College	1
Melville High School	1	Titirangi Rudolf Steiner School	1
Michael Park School	1	Waimea College	1
Mount Albert Grammar School	3	Waiuku College	1
Mount Maunganui College	1	Wellington Girls' College	1
Napier Girls High School	2	Western Springs College	2
New Plymouth Boys High School	3	Westlake Boys High School	2
New Plymouth Girls' High School	1	Whanganui High School	4
One Tree Hill College	3	Zayed College for Girls	1
Orewa College	4		