My Background & Overview of Next Gen Science

- Roy Myose's background: B.S. to Ph.D. in aerospace engineering
- Academic experience: ~30 yrs teaching aerospace engineering
- Industry experience: ~2 yrs as a design & systems engineer with Hughes Space & Communications during the mid-1980's

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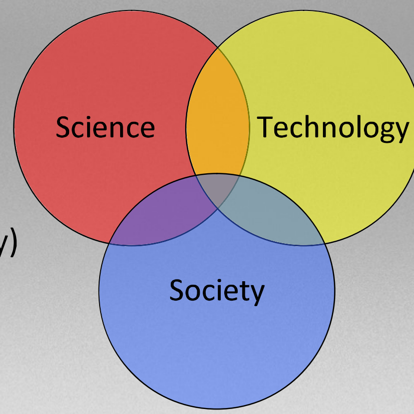
- Science & technology must work together for the good of society
- Complexity may be involved:
  - o Bioethics (science & society)
  - o Internet addiction (tech & society)
- Five scientific applications of GPS (www.scientificamerican.com/article/gps-is-doing-more-than-you-thought/)



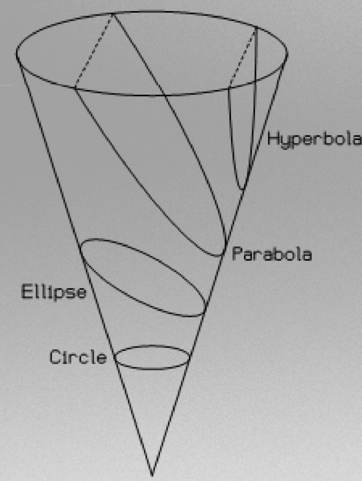
Why Engineering is a Part of Next Gen Science Education

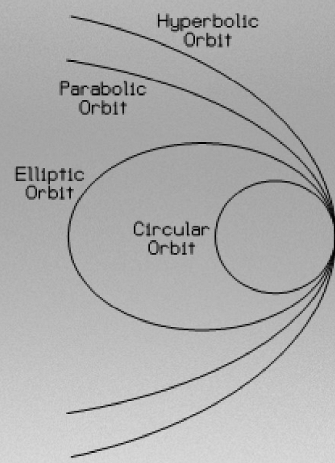
- Next Generation Science Standards (NGSS) Appendix I notes that:[1]
  - o *Students will gain insights into how science & **engineering** can be instrumental in addressing major societal **challenges***
  - o *Engineering has much in common with science, but engineering design has a **different purpose** & product than scientific inquiry*
- Quote by Theodore von Kármán: *"scientists study the world as it is, engineers create the world that never has been."*
  - o Engineers utilize scientific concepts (i.e., applies them) to **create** a solution (to a societal problem)
- The next few slides will illustrate the space science concept vs. space engineering application difference
- Then the engineering process consisting of problem definition, understanding constraints, and considering different solutions will be examined

[1]NGSS Appendix I (www.nextgenscience.org/sites/default/files/resource/files/Appendix%20I%20-%20Engineering%20Design%20in%20NGSS%20-%20FINAL_V2.pdf)

Space Science Concept: Geometry of Orbit Types

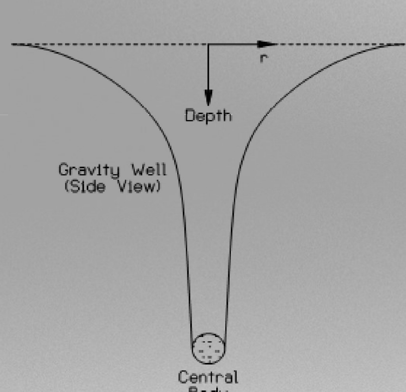
- Planetary orbits were defined by the Greeks ~1900 yrs ago
- Circular, elliptic, parabolic & hyperbolic orbit shapes can be formed from conic sections (i.e., slicing a cone)

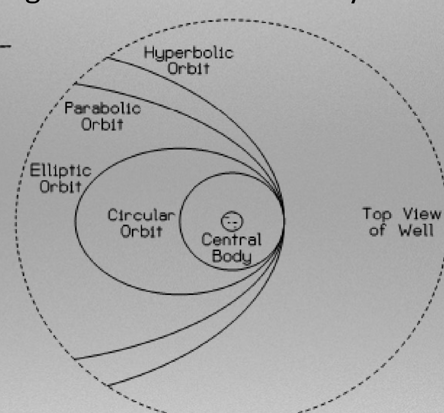




Space Science Concept: Conservation of Energy

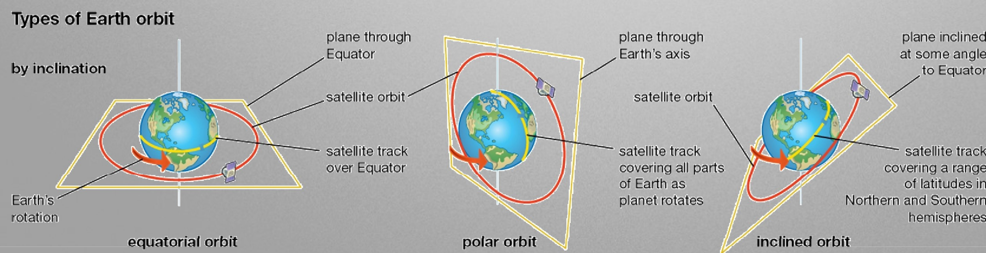
- Gravity well model (Vortx™) can simulate conservation of energy
- Depth of the well is inversely proportional to radius squared, which is the same form as the law of gravitation discovered by Newton



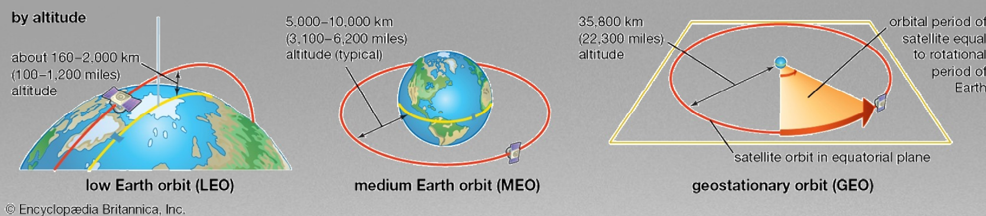


- Satellites in elliptic orbits trade potential energy (reducing its height above the Earth) for kinetic energy (increasing its speed)

Space Engineering Application: Defining Orbital Characteristics



- Northern latitudes are not visible from equatorial orbit – must be inclined

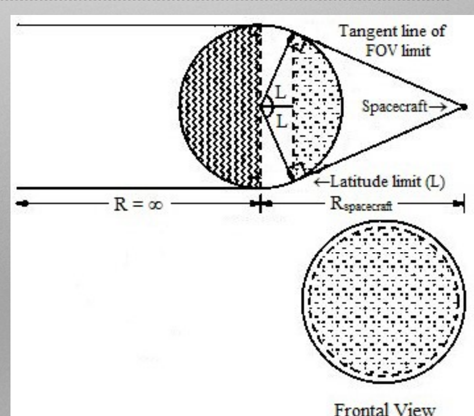


- Satellite in geosynchronous orbit appears stationary to a ground observer while satellites in low & medium orbits appears to travel fast to the east

Orbit types: https://cdn.britannica.com/47/73347-050-C10C7514/orbits-characteristics-satellite-shape-inclination-Earth-terms.jpg

Space Engineering Application: Field of View Constraint

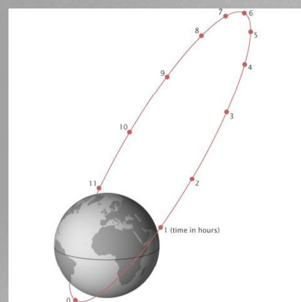
- North & south poles are visible when the spacecraft is located infinitely far away (shown on left)
- There are latitude angle limits ($\pm$L) for the Field of View (FOV) when the spacecraft is closer to Earth
  - o When R = 42,164 km (i.e., for Geosynchronous orbit), FOV is about $\pm 81^o$ (shown on right)

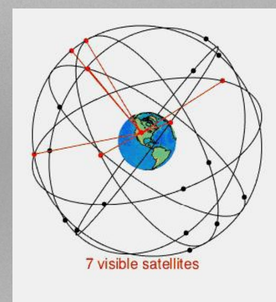


  - o Practical limit is even less than that since a ground observer at 81^o latitude can only see the spacecraft along the horizon, and any obstruction (such as a polar bear!) would obstruct this view
- Spacecraft in Geosynchronous orbit would not be visible by ground observers located in the far north (a challenge for the Russians!)

Space Engineering Application: Different Orbit Type Solutions

- Russian Molniya communication satellite is in an inclined highly elliptic orbit with a ~12 hour "hang time" over the northern latitudes (with a 2nd Molniya for 24 hr coverage)





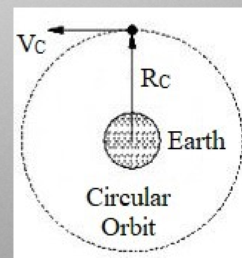
- A constellation of 24 Global Positioning Satellites (GPS) in Medium Earth Orbit (MEO) provides location info based on principle of triangulation (need > 3 satellites visible)

GPS & Molniya orbit figures from Wikipedia Commons

Overview of The Engineering Process

- In the previous slides, the difference between space science (concepts) vs. space engineering (applications) was illustrated
  - Science provided the concepts (i.e., how the universe operates) while engineering applied those concepts to achieve different kinds of solutions
  - E.g., communication satellite in Geosynchronous orbit (standard type) vs. Molniya orbit if northern latitudes are to be reached
- In the next few slides, the engineering process will be examined in more detail – the process includes:
  - Defining the problem, especially what is needed
  - Understanding constraints, especially the complexity involved
  - Considering different solutions, and then optimizing to obtain the best result

Problem Definition for Rocket: High Speed Needed For Orbit

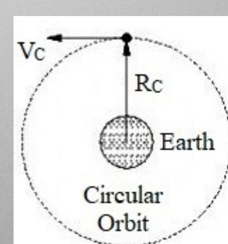


- A spacecraft must be traveling at high speed (i.e., velocity) in order to be in orbit
- Velocity required in a circular orbit is given by:

  $$V_C = \sqrt{g_H \times R_C} \text{ and } g_H = g_{\text{Sea Level}}\left(\frac{R_{\text{Earth}}}{R_C}\right)^2$$

  where $g_{\text{Sea Level}} = 9.81\text{m/s}^2$ & $R_{\text{Earth}} = 6{,}378{,}000\text{m}$
  - o The standard Low Earth Orbit (LEO) is defined to be at an altitude of H=185km which means that $R_C = R_{\text{Earth}} + 185{,}000\text{m} = 6{,}563{,}000\text{m}$
  - o This means that acceleration due to gravity at this altitude is $g_H = g_{\text{Sea Level}}(6{,}378{,}000/6{,}563{,}000)^2 = 9.26\text{m/s}^2$ (a reduction of 6%)
- Substituting these values results in a circular orbit velocity at LEO of $V_C \sim 7800\text{m/s}$ (i.e., ~28,000km/hr or ~17,400mph)
- A rocket must deliver the spacecraft to LEO altitude (185km) with this velocity (7.8km/s), but most importantly in correct direction

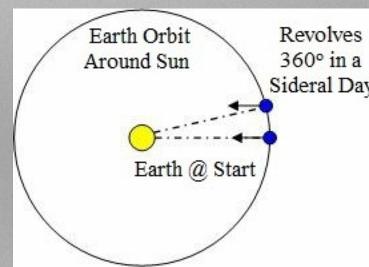
Constraints for the Rocket: Speed vs. Climb & Direction



- Two-fold objective for a rocket:
  - o Attain the high speed necessary for the orbit
  - o Climb to an altitude associated with that orbit
- Meeting this two-fold objective is difficult because direction for orbital velocity (at the end of climb) must be *perpendicular* to direction of climb
  - o Velocity increases as the rocket climbs, but it basically increases the speed in the direction it is traveling (i.e., in radial direction)
  - o On the other hand, direction required for the velocity upon orbit insertion (i.e., at the end of climb) must be *perpendicular* to the radius direction

Another Complexity Related to the Rocket's Requirement

- The Earth completes one revolution (360^o) in 23hrs 56min 4secs (i.e., 86,164 sec) – this is called the *sideral* day or period $T_{sideral}$
- Suppose we consider the situation with the Sun directly overhead
  - One sideral day later, the Earth moves along its orbit around the Sun by about ~1^o (i.e., ~360^o/365.25 days)
  - This means that the Sun is not directly overhead (as shown), but must rotate another ~1^o (i.e., ~4min more) before it is overhead – this total time period is the familar solar day of 24 hrs



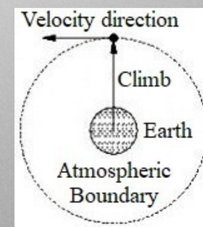
- Since the Earth rotates (360^o in 86,164 sec), the ground is moving
  - Rotation speed at the equator would be ($2\pi R_{Earth}/T_{sideral}$=) 464m/s
  - This is a "free" boost in speed if launch is made from the equator
- Even with this free boost, the rocket must still provide the remaining ~7340m/s increase in speed, and especially in the **correct** direction

Further Constraint for Rocket: Drag Slows Down the Vehicle

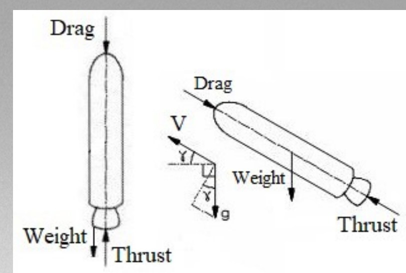
- The Earth's atmosphere thins out with altitude so there is no clear boundary defining the edge of the atmosphere
  - Decrease in density is exponential – slowly at lower altitudes & quickly (i.e., very thin) at moderate to higher altitudes
- As an aside, it is useful to define the altitude for edge of atmosphere to distinguish pilots from astronauts
  - An international organization setting standards defines the edge of the atmosphere to be 100km above the surface of the Earth
  - NASA defines the boundary differently, at 80km => some X-15 rocket plane pilots have been awarded astronaut wings
- Drag (force to overcome friction flying through the atmosphere) must be overcome with excess thrust which requires energy (i.e., fuel burn)
  - Drag is proportional to density so more fuel is required to fly in the lower part of the atmosphere
  - Thus, rocket should climb up quickly through the lower altitudes

Solutions for Rocket Trajectory & Gravity Turn Manuever

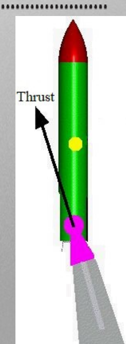
Some possible rocket trajectories during climb:



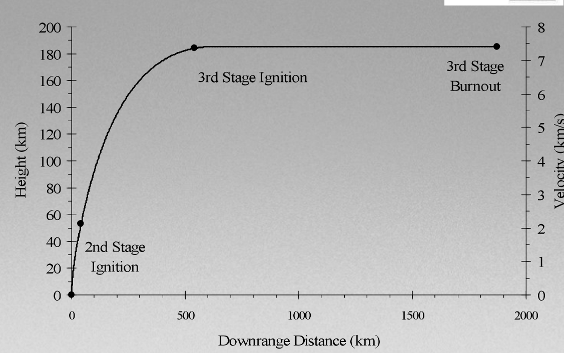
- Idea #1: Climb straight up to leave the atmosphere (where drag must be overcome) before turning 90^o => But turning suddenly will require lots of fuel burn to change the velocity's direction by 90^o
- Idea #2: Fly horizontally while *slowly* climbing => But this requires lots of fuel burn to overcome drag in denser part of atmosphere
- Idea #3: Climb up quickly to leave the denser part of the atmosphere then *slowly* turn horizontally
  - o At first glance, it might appear that fuel burn is required to turn rocket
  - o However, gravity (i.e., rocket weight) can be used as the force to turn it
  - o This gravity turn maneuver is "free" without any fuel burning "cost"



Rocket Solution Optimization: Variables for Gravity Turn



- Initiating the gravity turn requires a non-vertical thrust by *vectoring* the rocket nozzle for a short time as shown
- Variables associated with the gravity turn maneuver are:
  - o When to start the turn (i.e., after clearing launch tower)
  - o Turning amount (i.e., angle) of rocket nozzle *vectoring*
  - o Duration (i.e., length of time) of thrust *vectoring*
- Computer simulations are used to try different starting time, angle and duration of vectoring
  - o Computer simulations are non-physical form of experimentation
  - o Best solution shown =>



Gimbaled thrust figure from NASA.gov

Summary of Engineering Process in Rocket Trajectory Problem

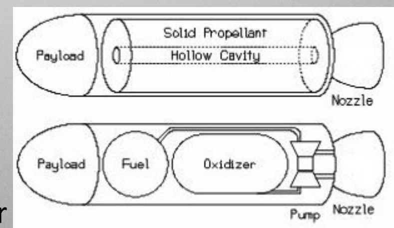
- Summary of how the standards-based system was used to solve the rocket trajectory problem
  - o ***Define the problem***: high speed needed to be in orbit – this must be provided by the rocket delivering the spacecraft
  - o ***Specify criteria & constraint***: velocity must be oriented vertically at the start of climb & horizontally at the end
  - o ***Generate & evaluate multiple solutions***: vary starting time, angle amount & time duration of thrust vectoring for turn
  - o ***Build & test "prototypes", and then optimize the solution***: computer simulation of rocket trajectory was used instead of actually flying rockets along different trajectories (because this would be very expensive to do)

Next Gen Science Standards Description of Engineering Process

- NGSS Appendix I notes that students should be able to:[1]
  - o *"**Define problems** – situations that people wish to change by …"*
  - o *"**Specifying criteria & constraints** for acceptable solutions,"*
  - o *"**Generating & evaluating multiple solutions**,"*
  - o *"**Building & testing prototypes**, and"*
  - o *"**Optimizing a solution**."*
- Recall Theodore von Kármán's quote: *"Scientists study the world as it is, engineers create the world that never has been."*

[1]NGSS Appendix I (www.nextgenscience.org/sites/default/files/resource/files/Appendix%20I%20-%20Engineering%20Design%20in%20NGSS%20-%20FINAL_V2.pdf)

Trial & Error Process & History of Rocketry



- Two different types of rockets are in use today for delivering spacecraft to orbit
  - o Solid propellant rockets (upper figure)
  - o Liquid propellant rockets (lower figure)
- Solid propellants are basically gun powder
  - o Developed by the Chinese as fireworks rockets ~1000 years ago
  - o Poor control until recently (cf. Rockets Red Glare in National Anthem[1])
  - o *Perhaps consider tie in of these two topics with history lesson?*
- Solid propellants are relatively safe, storable, but not very powerful
- Liquid propellants are more powerful, but often require refrigeration
  - o Developed by Robert Goddard, an American ~100 years ago
  - o Improved through trial & error process by Wernher von Braun of Germany (who came to U.S. after WWII) & Sergei Korolev of Russia

[1]"Rockets that Inspired Francis Scott Key" (https://www.airspacemag.com/history-of-flight/rockets-inspired-francis-scott-key-180952399/)

Internal Structure of Rocket

- Basic structure of rocket consists of
  - o Lengthwise stringers to carry the load
  - o Thin panels to form exterior shape
  - o Rigid frames to maintain shape (if panels can't keep shape)
- Different failure modes possible

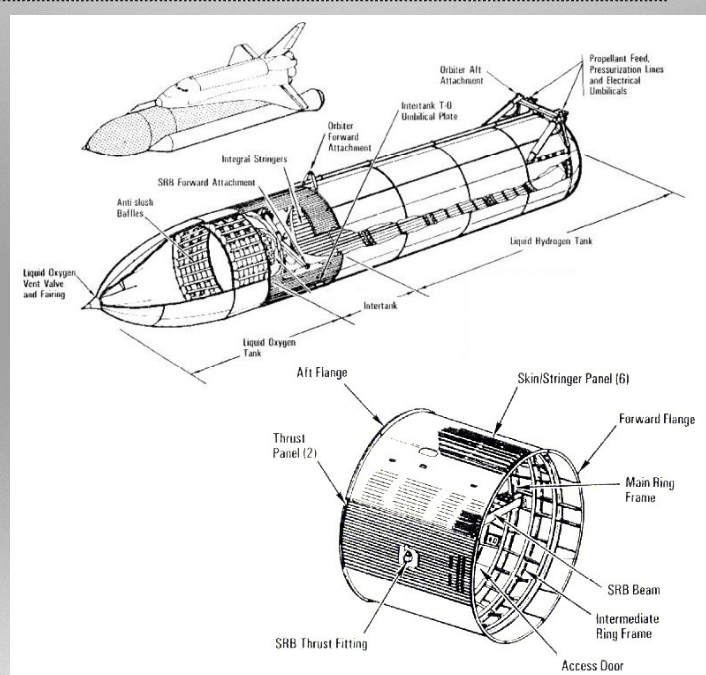
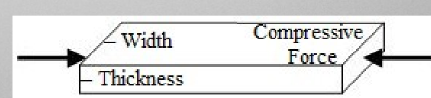


Figure from NASA.gov & wikipedia commons

Failure Modes & Material Properties

- There are multiple ways that a structure can fail, for example:
  - o Exceed major load carrying limit – lengthwise load in compression (pushing together) or tension (pulling apart) is too large
  - o Moderate loads can cause buckling – external skin panels will wrinkle which then affects the aerodynamic drag of the vehicle
  - o Cyclic (repeated small) loads can cause joints to be fatigued & fail – rivets & bolts do not normally fail at small loads, but it can fail if it undergoes this loading repeatedly
- These failures are a function of the properties of the material being used to manufacture the structure
  - o Titanium – very high strength & very expensive, but lightweight
  - o Stainless steel – high strength & high cost, moderate weight
  - o Aluminum – moderately high strength, moderate cost, lightweight
  - o Wood – reasonable strength (~1/10 of aluminum), low cost & wt
  - o Paper is processed from wood & has lower strength

Failure Modes & Material Properties



- Strength of material is characterized by the maximum force load divided by the area (i.e., width x thickness)
  - o Wood has an ultimate compressive strength of ~4000+ lb/in^2
  - o Compressive strength of paper is not easily found in the literature, but a rough guess is ~½ that of wood or ~2000 lb/in^2*
- A sheet of 8½” x 11” paper is ~0.004” thick & weighs ~0.01 lb
  - o If this paper is oriented in 8½” side, it has an area of 8½” x 0.004” = 0.34 in^2 so it should support a maximum of (2000 x 0.34 =) 68 lb
  - o If two sheets of paper are used, it should, in theory, support a load of 136 lb without crumpling & being crushed in failure
- Two sheets of paper weigh ~0.02 lb (or 0.32 ounce) plus some material to fasten them together for mutual support => ~0.5 ounce
  - o Limiting max load to 100 lb & assuming 0.5 ounce (i.e., 1/32 lb) means a strength to weight ratio of 3200 is possible with paper

*Best guess is based on fact that tensile strength of paper is about half that of wood

Standards-based Space Science (Engineering) Activity

- Challenge: keep a “heavy” object a few inches above a table top [*this defines the problem*]
- Constraint: use only two pieces of paper & some tape to keep object at least 5½” above the table [*this specifies the detailed criteria & constraints*]
- Consider different shapes & sizes to solve the problem, then build & test them, & follow up with refinements for an optimal solution to the problem [*this is steps 3, 4, & 5 in the Engineering Process*]
  - Computer simulations are often involved in steps 3 & 4 while manufacturing methods are important in step 5