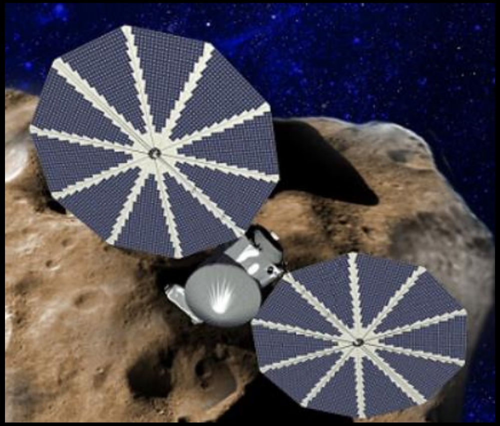
From Basking Ridge to the Jupiter Trojans

Jacob Englander

Class of 2002



Who am I, and why am I here?

- Ridge High School Class of 2002
    - One of six students in Mr. Gilmore’s original AP Physics C class
    - 4-year member of the track and cross country teams under Mr. Mooney.
        - For those of you who know Coach Gilhuley, she and I were teammates!
- B.A. Physics from Grinnell College, 2006
- M.S. Aerospace Engineering, University of Illinois, 2008
- Ph.D. Aerospace Engineering, University of Illinois, 2013

Goddard Space Flight Center

Goddard Space Flight Center

- Largest of 10 NASA Centers
  - Over 10,000 employees
- Goddard is composed of four campuses
  - Main campus in Greenbelt, MD
  - Wallops Flight Facility on Wallops Island, VA
  - Goddard Institute for Space Science in New York, NY
  - Independent Validation and Verification in Fairmont, WV
- Goddard does significant work in:
  - Science
  - Spacecraft design and construction
  - Space operations
  - Robotics
  - Launch
- Goddard is the only NASA center that is involved in everything that NASA does

Science at Goddard

- Astrophysics
  - Hubble Space Telescope, James Webb Space Telescope
- Earth Science
  - Landsat, GPM, climate modeling
- Heliophysics
  - MMS, SOHO, STEREO
- Planetary Science
  - Lunar Reconnaissance Orbiter, Maven, OSIRIS-REX, Lucy

Navigation and Mission Design Branch

- “Navigation” is the science and engineering of asking “where is the spacecraft in the solar system, relative to the Earth and other objects?”
- “Mission Design,” also called “Trajectory Design” is the science and engineering of figuring out how to get from where you are to where you want to go.
- “Mission Operations” is the engineering of actually flying the spacecraft, day-to-day
- The Navigation and Mission Design Branch consists of about 140 people:
  - ~100 mission operators
  - ~40 mission design and navigation analysts

Global Trajectory Optimization Lab

- We are a small group within the Navigation and Mission Design Branch
- Our task is:
  - Design trajectories for interplanetary missions and potential missions
  - Develop new techniques in trajectory design and optimization
  - Develop new software tools
  - Advise graduate students who we some-day hope to recruit
  - Optimize the trajectory for NASA’s Lucy mission to the Jupiter Trojans

Global Trajectory Optimization Lab

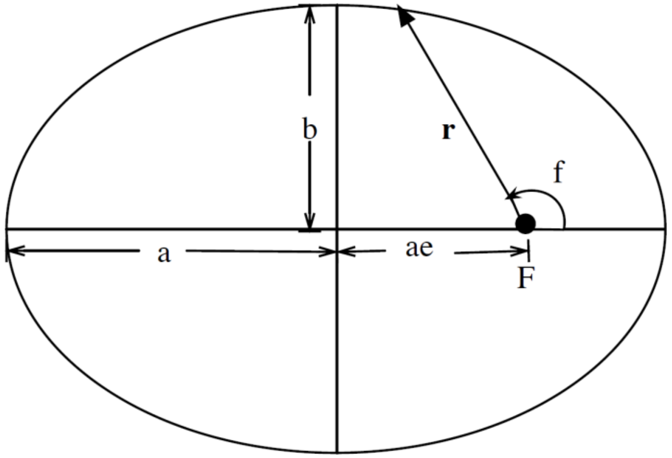
The Physics of Spaceflight (Analytical)

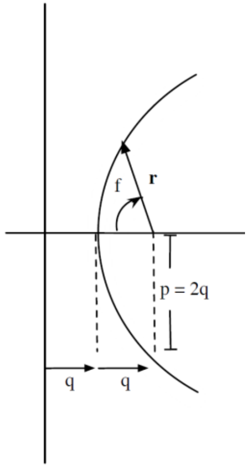
$$\ddot{\boldsymbol{x}} = \frac{-\mu_{CB}}{r_{CB}^3}\boldsymbol{r}_{CB}$$

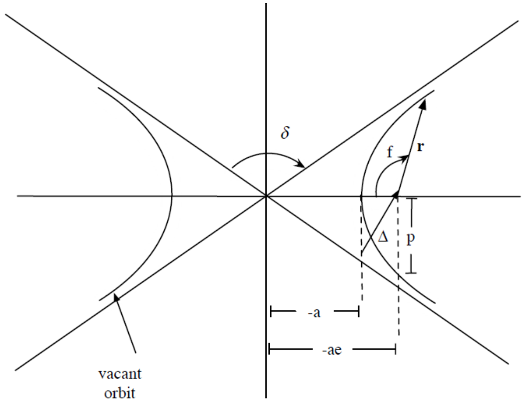
2-body central force gravity
(Newton)

All body orbits are conic sections
(Kepler)

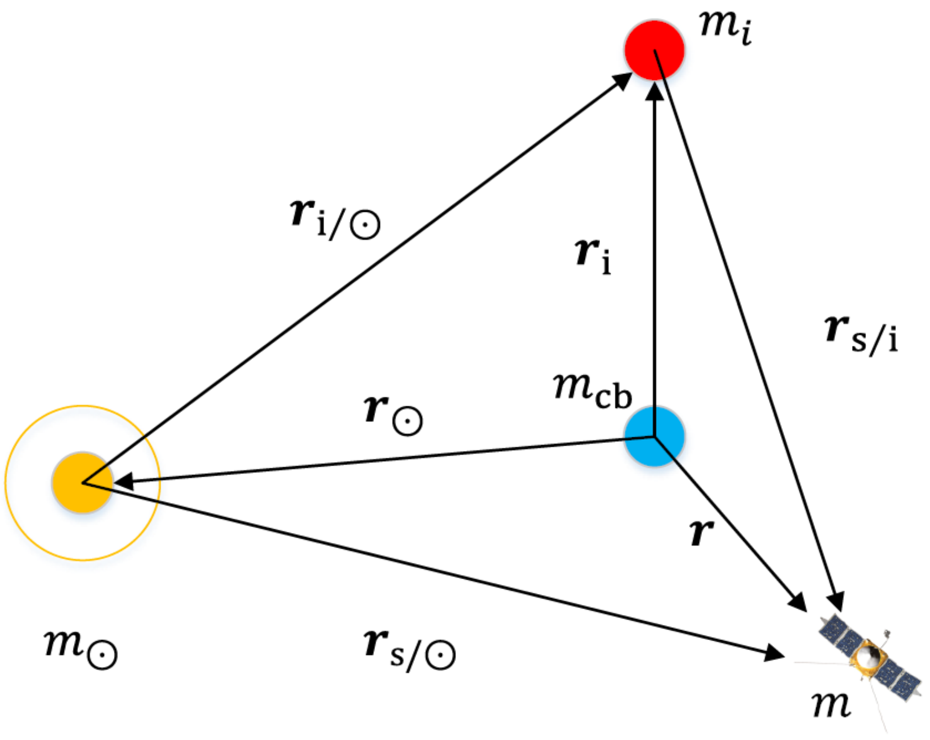
The position and velocity of the spacecraft may be propagated by solving Kepler's equation.







The Physics of Spaceflight (Reality)



$$\ddot{\boldsymbol{x}} = \frac{-\mu_{CB}}{r_{CB}^3}\boldsymbol{r}_{CB} + \frac{-\mu_{CB}}{r_{3b}^3}\boldsymbol{r}_{3b} + \mathbf{F}_{\mathrm{SRP}} + \mathbf{F}_{\mathrm{thrust}} + \cdots$$

No analytical solution!

The Physics of Spaceflight (The Rocket Equation)

$$m\frac{dv}{dt} = v_{exh}\frac{dm}{dt}$$

Differential form

If you assume that the maneuver is an impulse, you can integrate this analytically.

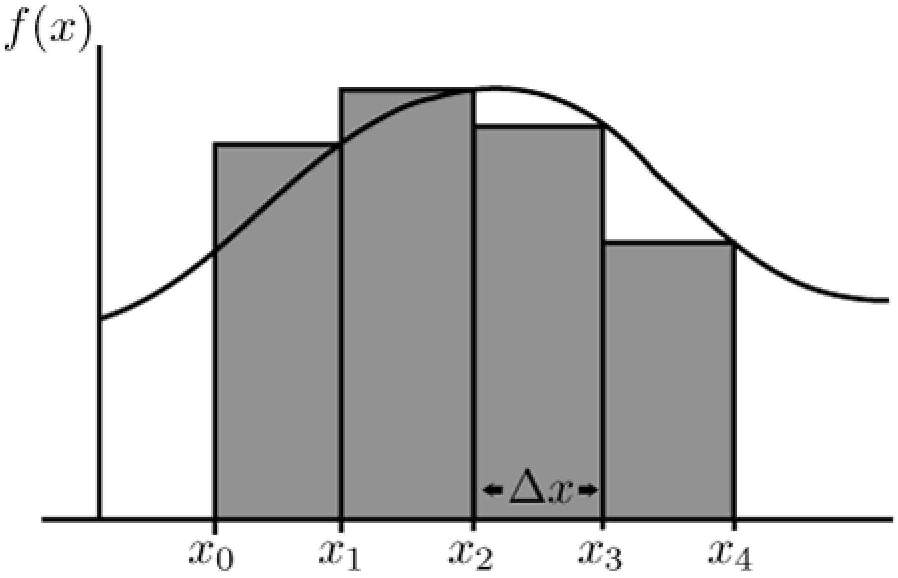
$$\Delta v = v_{exh}\ln\left(\frac{m_f}{m_0}\right)$$

Exponential form

- But in the real world, maneuvers are not impulses.
- High-thrust chemical propulsion maneuvers happen in minutes to hours.
  - The impulsive approximation is acceptable.
- Low-thrust electric propulsion maneuvers take weeks, months, or even years!
  - There is no analytical solution; we must integrate numerically.

The Physics of Spaceflight (numerical integration)

- Numerical integration methods are used when no analytical solution is possible.
- In Calculus class, you learned the simplest of these (Riemann sums, trapezoid rule, *etc*.)
- There exist many numerical integration methods, some of which are very complicated but achieve excellent accuracy.



Global Trajectory Optimization Lab

What is optimization?

- Finding the "best" way to do something:
  - Minimum propellant
  - Maximum final mass
  - Minimum time
- We must formulate and solve the following problem:

Minimize $f(\boldsymbol{x})$

Subject to:

$$\boldsymbol{x}_{lb} \leq \boldsymbol{x} \leq \boldsymbol{x}_{ub}$$
$$\boldsymbol{c}(\boldsymbol{x}) \leq \boldsymbol{0}$$
$$\boldsymbol{A}\boldsymbol{x} \leq \boldsymbol{0}$$

where:

$\boldsymbol{x}_{lb}, \boldsymbol{x}_{ub}$ are lower and upper bounds on the decision variables

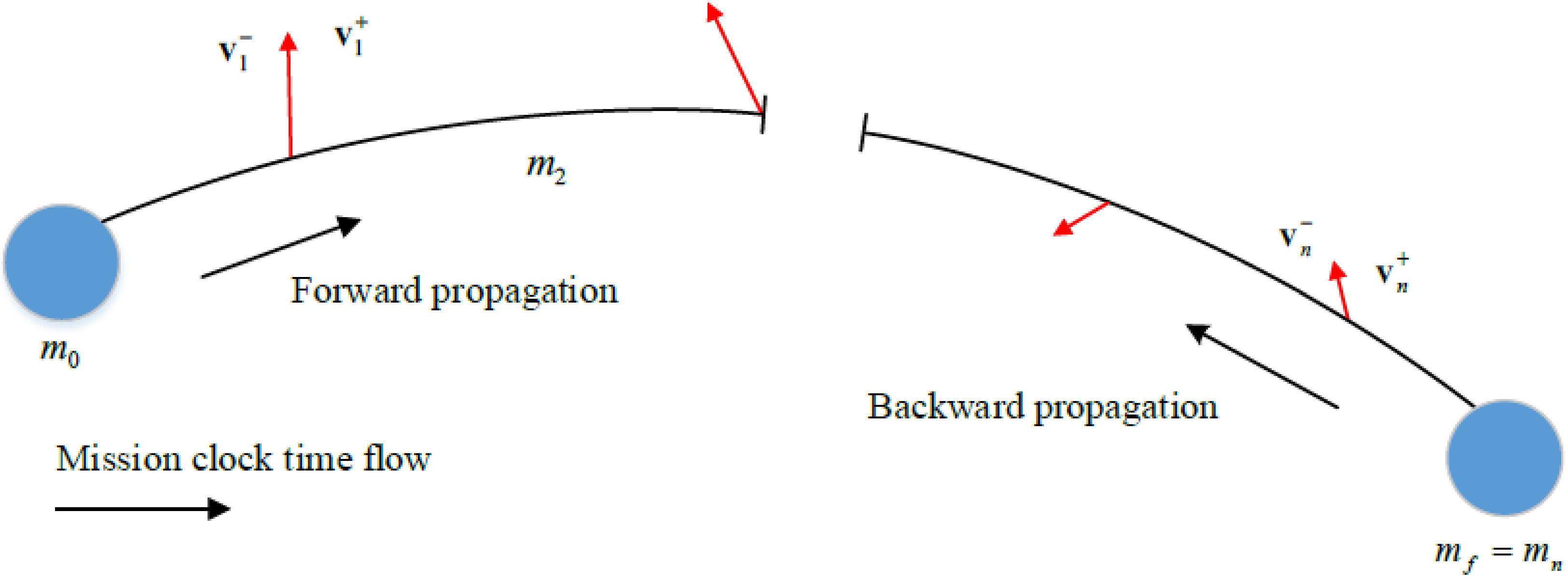
$\boldsymbol{c}(\boldsymbol{x})$ is a vector of nonlinear constraints

$\boldsymbol{A}\boldsymbol{x}$ is a vector of linear constraints

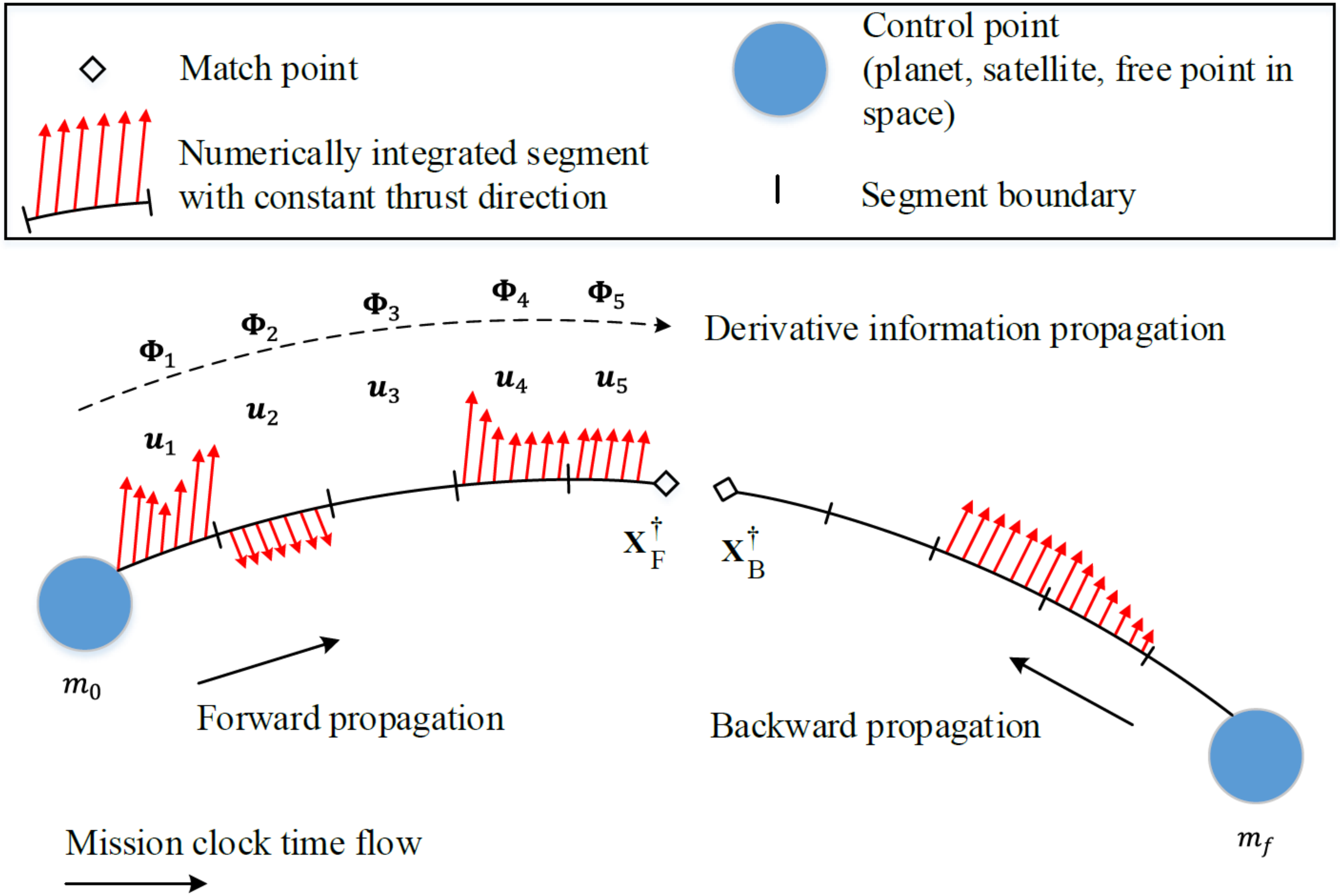
Gradient-Based Local Optimization

- In calculus, you learned how to find the minimum of a function:
  - $f'(x) = 0$ *necessary condition*
  - $f''(x) > 0$ *sufficient condition*
- But, our function has many variables, expressed as the vector **x**
- We also have many nonlinear constraints $\boldsymbol{c}(\boldsymbol{x}) \leq \mathbf{0}$
- This is called a *nonlinear programming problem* (NLP)
- There are many hundreds of PhD dissertations written on how to solve NLP problems, but in a nutshell:
  - Determine the gradients of the objective function $f(\boldsymbol{x})$ and the constraint functions $\boldsymbol{c}(\boldsymbol{x})$
  - Perform a *line search* along the gradient until the objective function and constraints stop improving
  - Repeat the process until the necessary and sufficient conditions of optimality are satisfied

Two-Point Shooting Transcription for Trajectory Optimization (high-thrust chemical propulsion)



Two-Point Shooting Transcription for Trajectory Optimization (low-thrust electric propulsion)



◇ Match point

Numerically integrated segment with constant thrust direction

● Control point (planet, satellite, free point in space)

| Segment boundary

Gravity Assist Maneuver

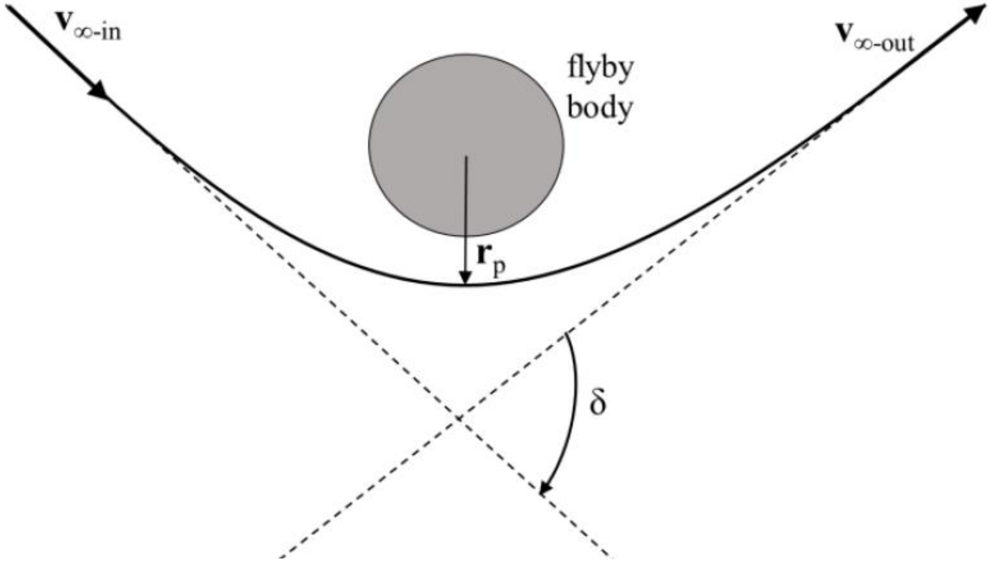
- We can use a planet's gravity to change the spacecraft's trajectory in interplanetary space.
- The spacecraft is on a hyperbolic orbit with respect to the planet.
- Energy is conserved in the reference frame of the planet:

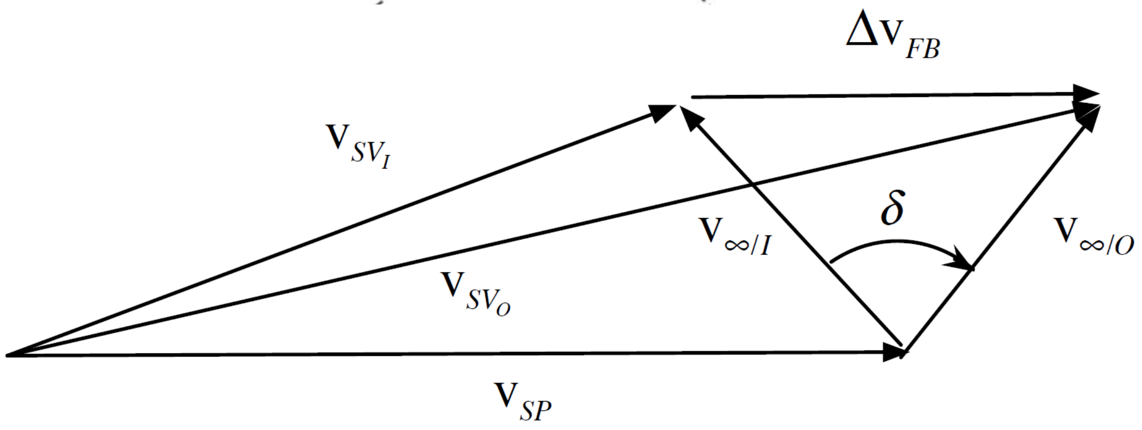
$$v_\infty^+ = v_\infty^-$$

- Energy is conserved in the reference frame of the sun because the spacecraft either takes energy from or gives energy to the planet.
- The turn angle may not be so tight as to require that we pass through the planet:

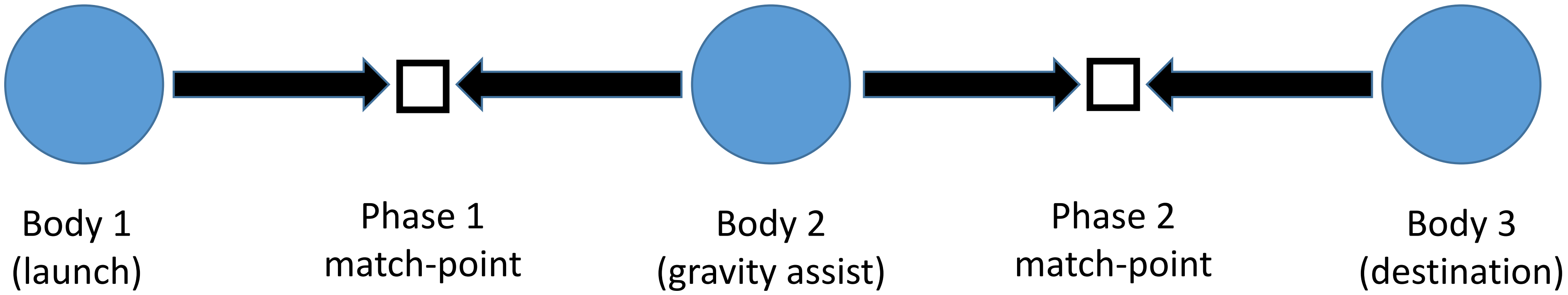
$$h = \frac{\mu_{planet}}{v_\infty^2}\left[\frac{1}{\sin\left({}^{\delta}/_{2}\right)} - 1\right] - r_{planet}$$

$$\delta = acos\left(\frac{\boldsymbol{v}_\infty^-}{v_\infty^-} \cdot \frac{\boldsymbol{v}_\infty^+}{v_\infty^+}\right)$$





Two-Point Shooting Transcription for Trajectory Optimization (multi-phase mission)



Body 1
(launch)

Phase 1
match-point

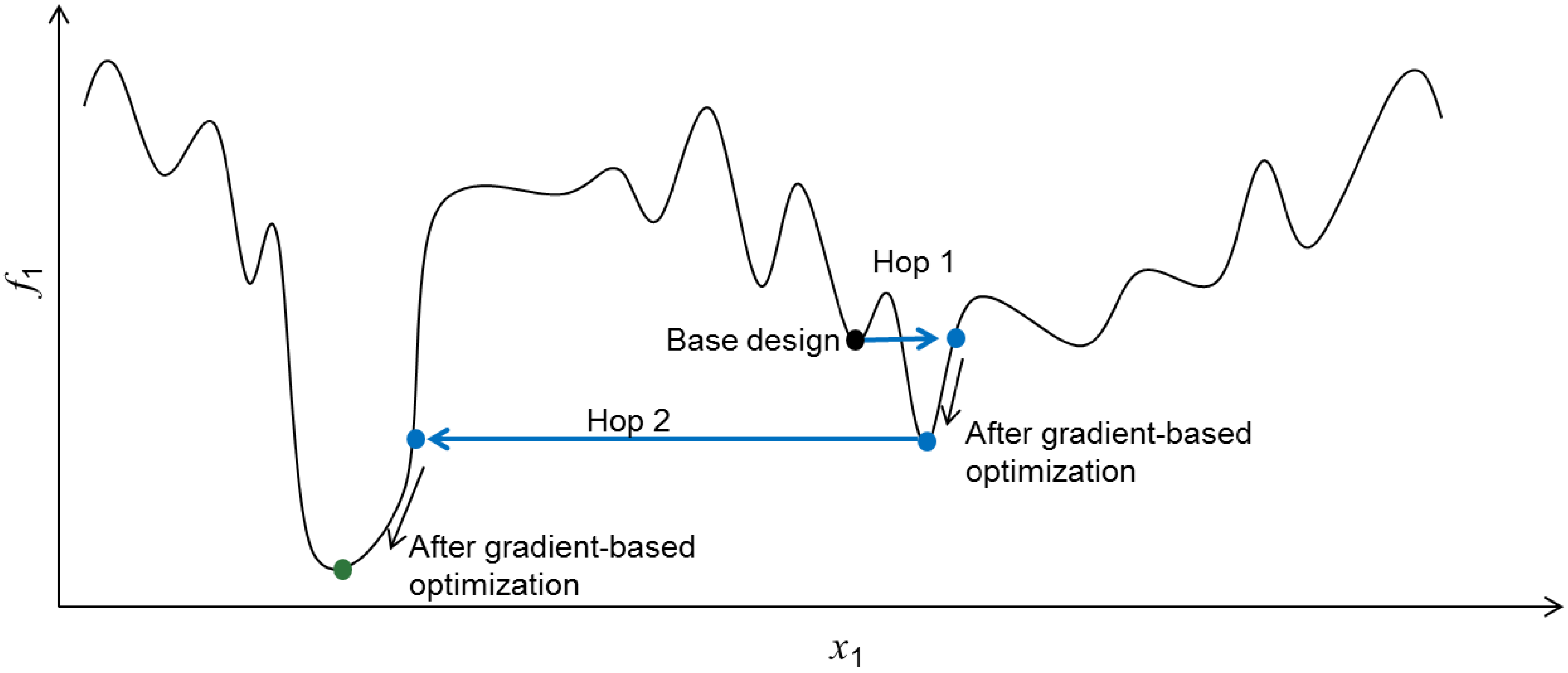
Body 2
(gravity assist)

Phase 2
match-point

Body 3
(destination)

Global Trajectory Optimization Lab

Stochastic Global Search via Monotonic Basing Hopping

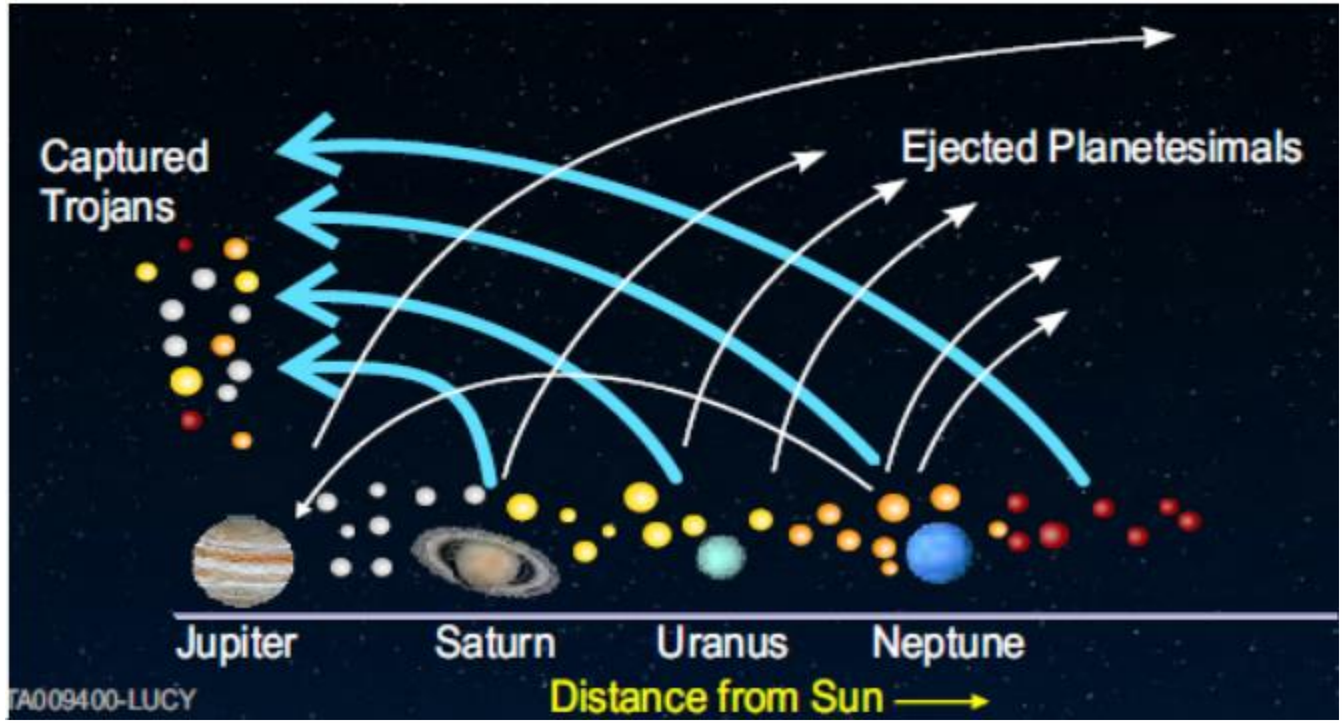


Time for an example…

Lucy: Exploring the Diversity of the Jupiter Trojans

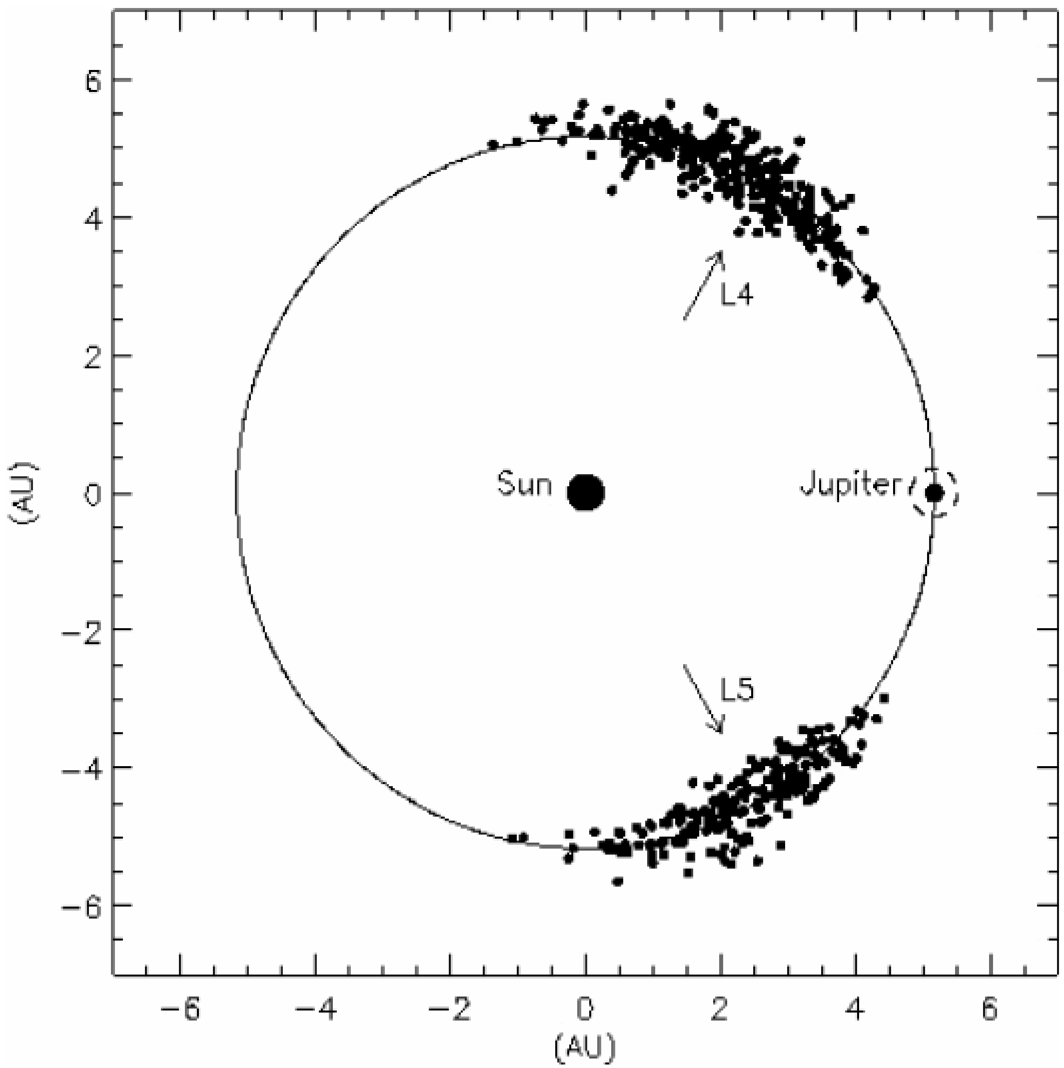
Gas giant migration and the Nice model

- What happened after the planets formed?
- Gravitational interactions among the giant planets caused them to migrate outward from the sun to their current orbits and, temporarily, drove Uranus and Neptune into eccentric orbits.
- As the gas giants moved outward, they scattered the remaining planetesimals in the outer solar system.
- Most of those planetesimals were ejected from the solar system, but some migrated inward…

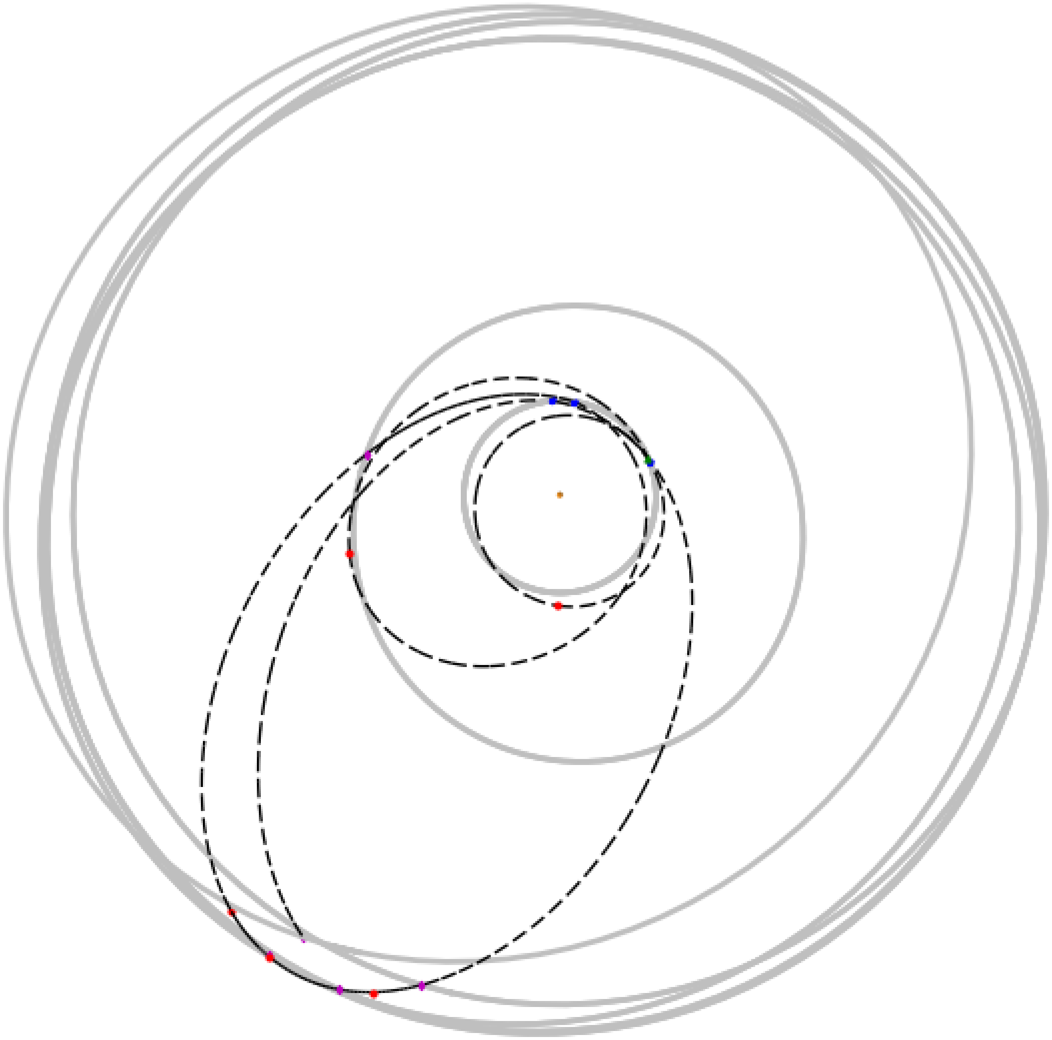


Hal Levison, Lucy PI and author of the Nice model

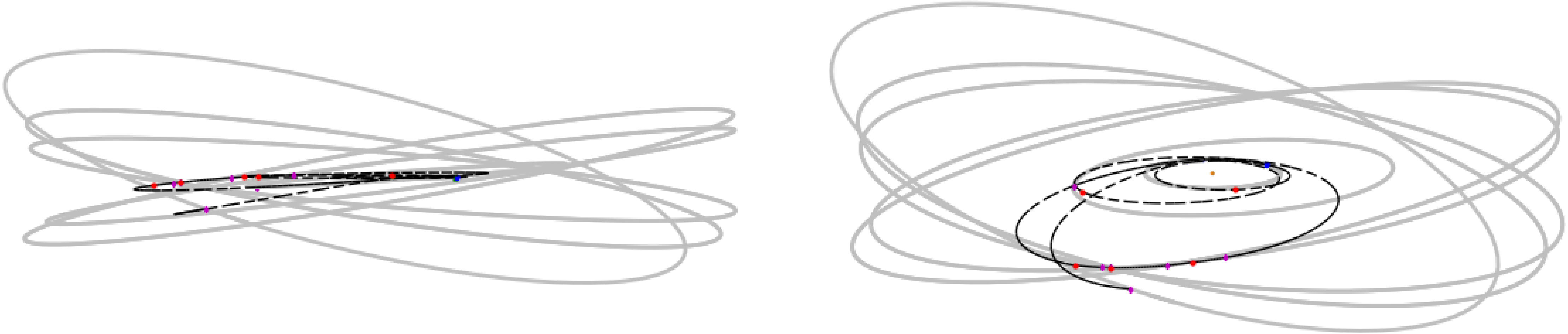
Jupiter and the Three Body Problem



Lucy: A Sun/Jupiter L4-L5 Cycler



Lucy Trajectory (from the side)



Lucy’s targets span the diversity of the Trojan Swarms

- 52246 Donaldjohanson is a main-belt object that serves as an engineering dress rehearsal for Lucy’s Trojan encounters.
- 3548 Eurybates is a large, rare C-type and the parent body of the only known collisional family in either Trojan swarm.
- 15094 Polymele is a small P-type, possibly a fragment from some long-ago collision.
- 11351 Leucus is a medium-size D-type with a very slow rotation period – almost three weeks! It may have a moon…
- 21900 Orus is a large D-type that is typical of much of the Trojan population.
- 617 Patroclus-Menoetius is an equal mass binary P-type and is unique among the Trojans…but resembles outer solar system objects that we can only see in telescopes!

Lucy Trajectory as an Optimization Problem

- We want to maximize the mass available for scientific instruments.
- This is a balance between the initial velocity imparted by the launch vehicle and the maneuvering done by the spacecraft’s thrusters.
- We also have to make sure that any propellant used by the spacecraft fits in the tank…
- …and we have to satisfy the trajectory continuity and flyby feasibility constraints that we discussed several slides ago.
- The final Lucy trajectory is the globally optimal solution to this optimization problem.

Lucy is a mission across generations of scientists and engineers

	Year	Hal Levison	Jacob Englander	You
Today	2017	58	33	18
Launch	2021	62	37	22
Earth Gravity Assist 1	2022	63	38	23
Earth Gravity Assist 2	2024	65	40	25
Donaldjohanson	2025	66	41	26
Eurybates	2027	68	43	28
Polymele	2027	68	43	28
Leucus	2028	69	44	29
Orus	2028	69	44	29
Earth Gravity Assist 3	2030	71	46	31
Patroclus-Menoetius	2033	74	49	34

What you need to know to do this job

- Physics
- Mathematics
- Computer science
- Oral communication
- Written communication
- Teamwork

These are **equally** important and you need to learn all of them!

Conclusion

- There are many great adventures that you can devote your life to – this is mine.
- No matter which adventure you choose, your Ridge education in science, mathematics, computer science, writing, and teamwork will serve you well.
- The purpose of NASA is to advance the frontier of human knowledge. Studying the structure and history of the solar system is just one of many ways that we do that.
- By the time you are my age, Lucy will be closing in on Patroclus-Menoetius…will any of you be working in the control room with me?