Granular Materials Research in Lunar Gravity

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Why do research in lunar gravity?

Experiments in a wide range of environments are key to understanding granular dynamics, enabling us to

- discover new phenomena
- develop robust & realistic models of granular dynamics

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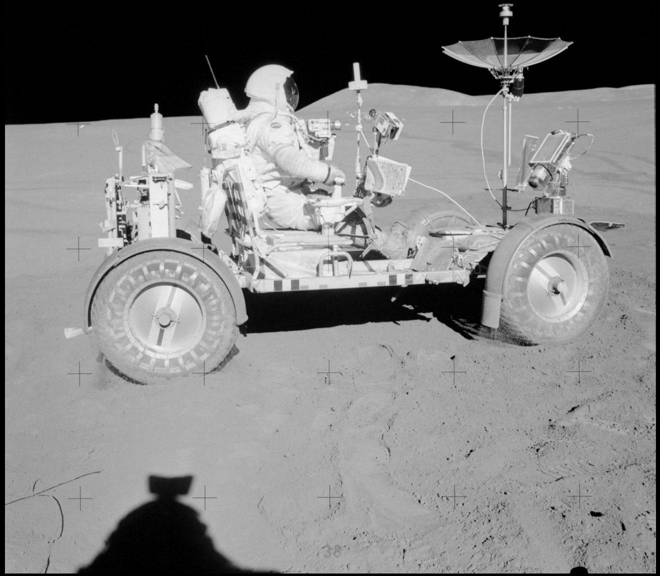
- improve interpretation of planetary geomorphology
- create safe conditions for in-situ resource utilization & human/robotic exploration



NASA/JSC (1971)

How we became experts on granular materials

Great Mosque, Mali Ruud Zwart
https://commons.wikimedia.org/w/index.php?curid=3326719

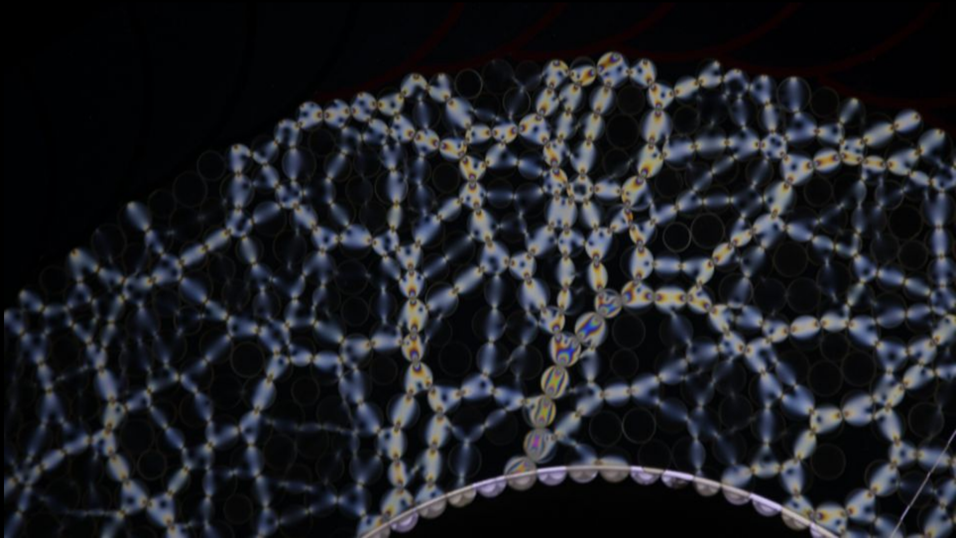
Statue being transported on lubricated sand
Al-Ahram Weekly 5-11 August 2004
Fall et al. *Phys. Rev. Lett.* (2014)

Taos Pueblo, New Mexico
John Mackenzie Burke
https://commons.wikimedia.org/w/index.php?curid=78067130

Properties of grains ➛ bulk granular materials

- Size
- Shape
- Friction coefficient
- Roughness
- Density
- Stiffness
- Adhesion
- Liquid bridges
- …

- Elastic modulus
- Tensile strength
- Flowability
- Settling rates



Gravity changes mechanical rigidity & sound speed

lower gravity

⇩

less-compacted grains

⇩

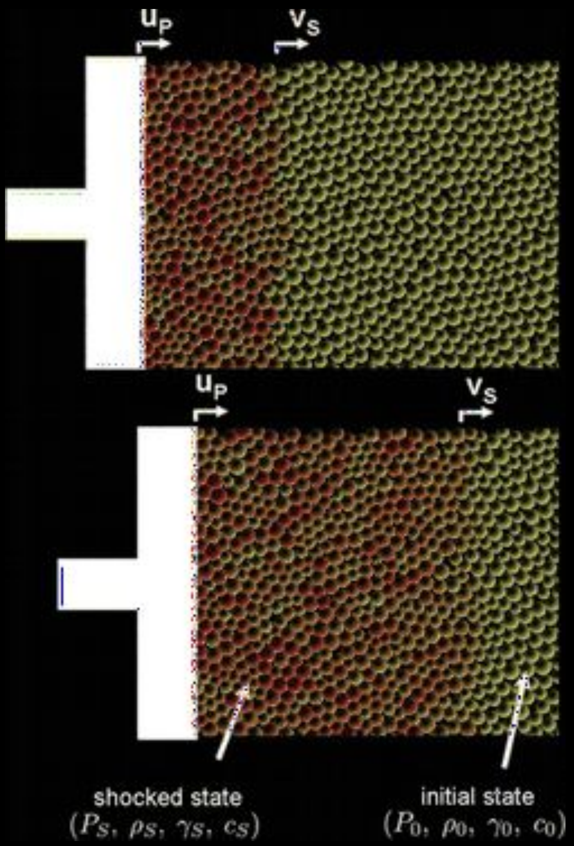
lower rigidity modulus

⇩

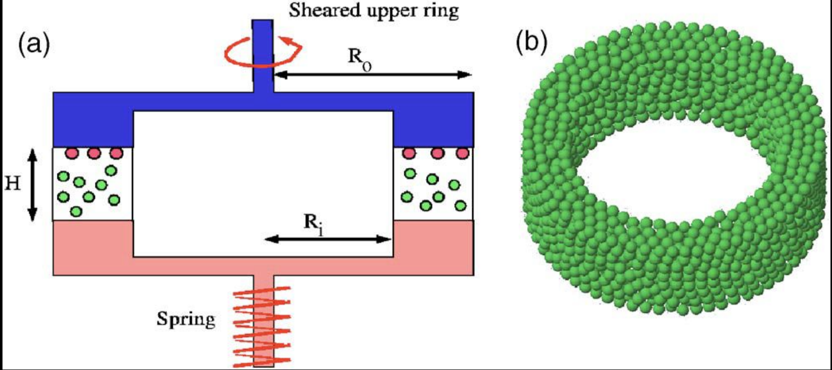
slower sound speed

Numerical simulations by

Gómez, Turner, van Hecke, Vitelli. *Phys. Rev. Lett.* (2012)



Gravity nontrivially changes flow dynamics



Numerical simulations by
Baran & Kondic. *Physics of Fluids* (2006)

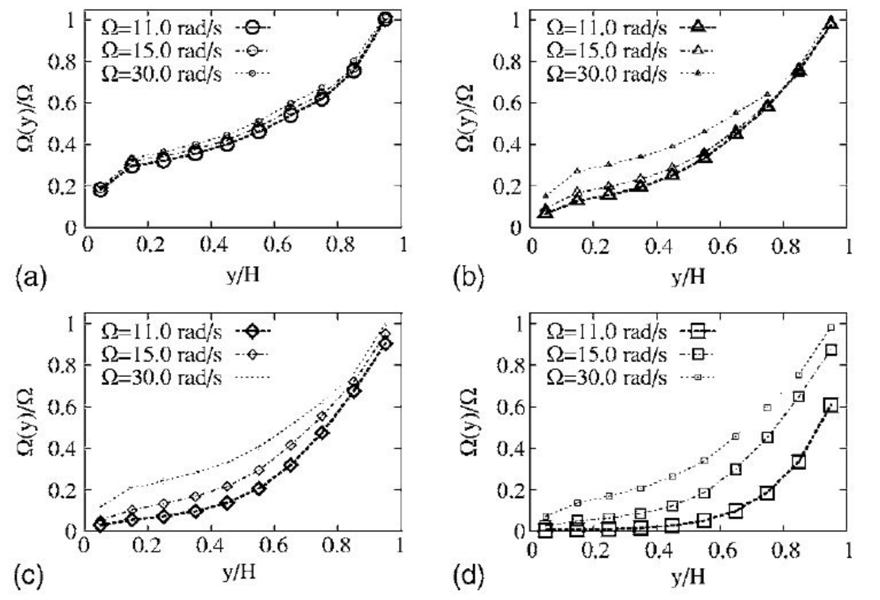
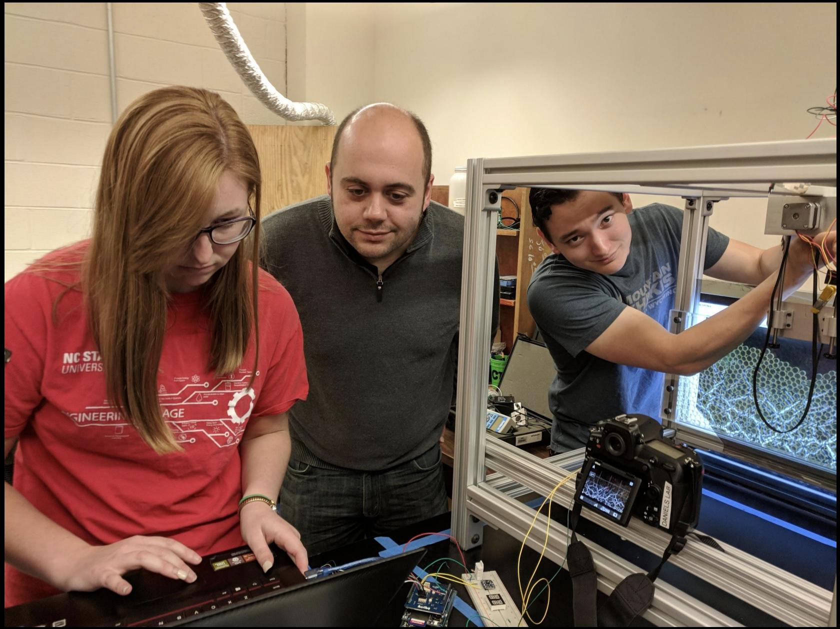


FIG. 2. Velocity profiles for different Ω's and for (a) zero g, (b) Moon gravity (g=162 cm/s^2), (c) Mars gravity (g=373 cm/s^2), and (d) Earth gravity (g=981 cm/s^2). The shearing wall is at y/H=1.

Example: lessons from low-gravity experiments

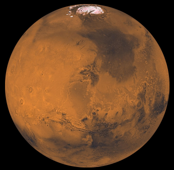


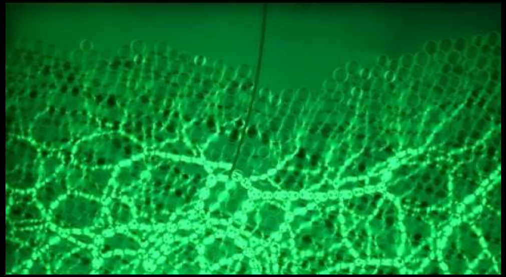
NASA Grant
80NSSC18K0269
(REDDI)

Gravitational acceleration controls probe dynamics

Mars

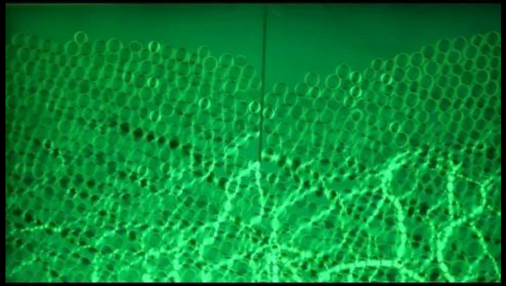
~ ⅖ g





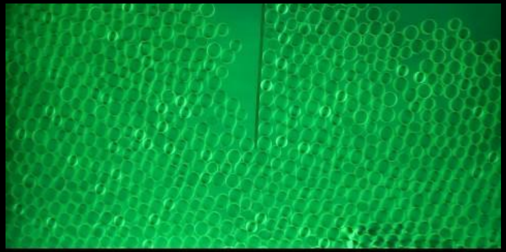
Moon

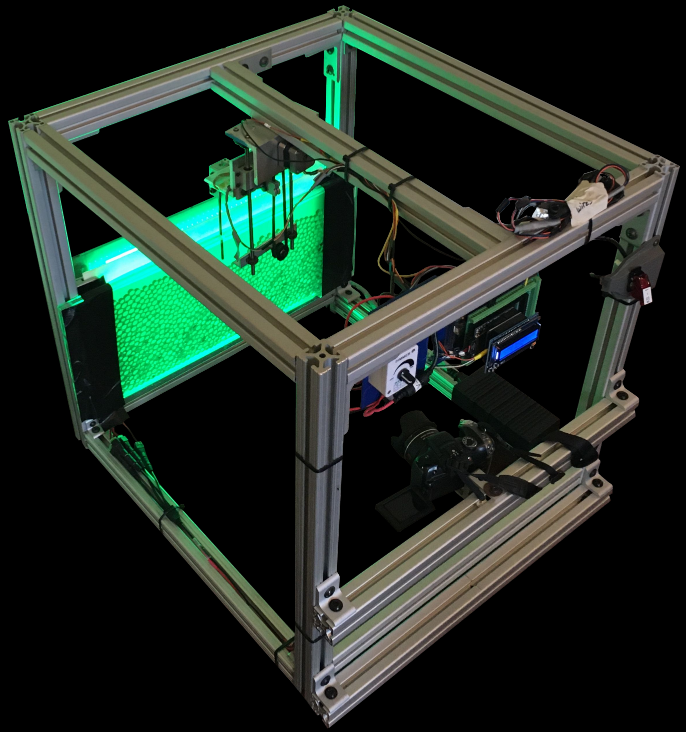
~⅙ g



Asteroid

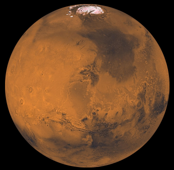
microgravity



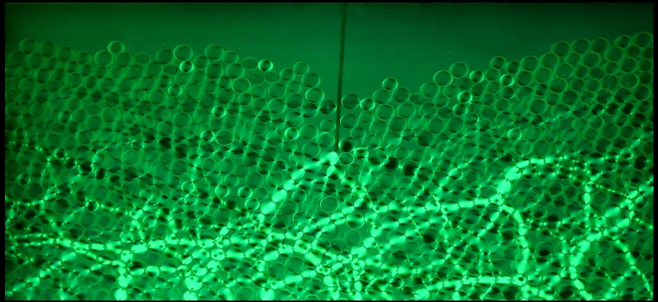


Featherstone et al.
arXiv: 2011.12890

Gravitational field controls probe dynamics

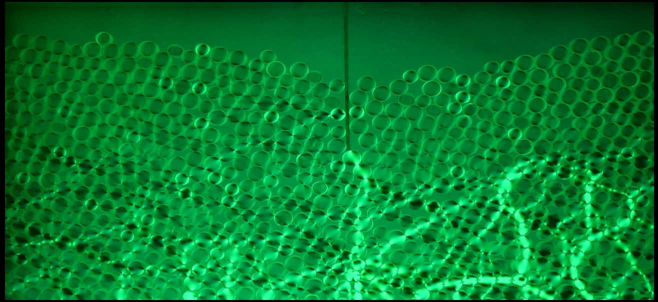
Mars 

~ ⅖ g



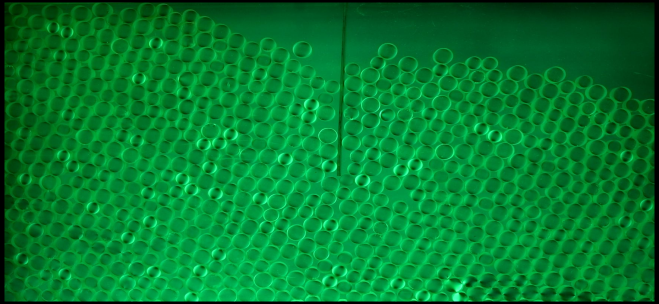
Moon 

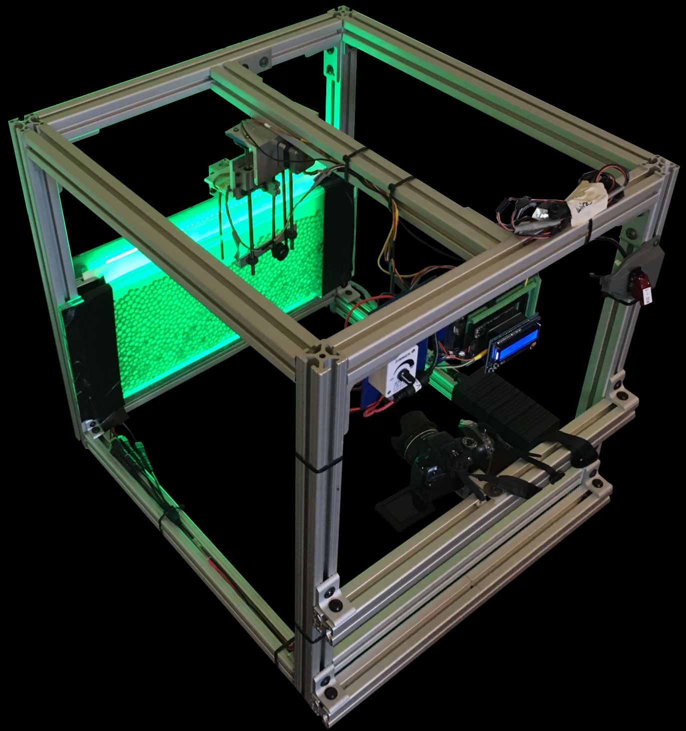
~⅙ g



Asteroid 

microgravity





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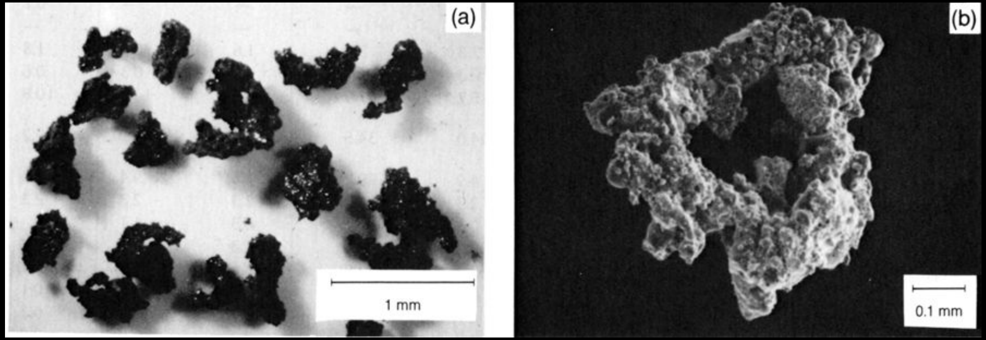
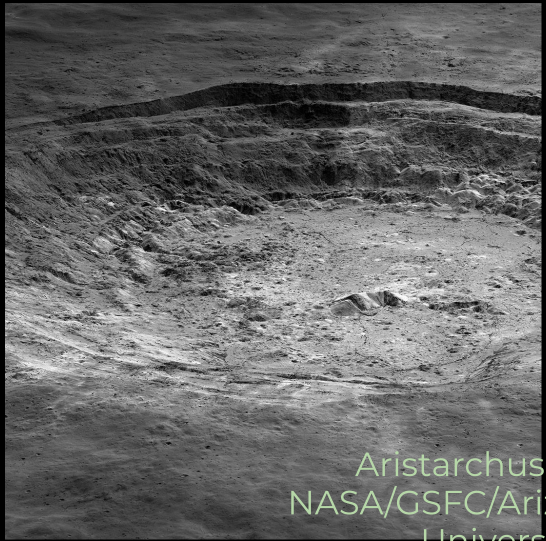
Apollo 11





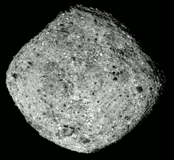
Aristarchus crater
NASA/GSFC/Arizona State University

Heiken, Vaniman, French. *Lunar Sourcebook* (1991)

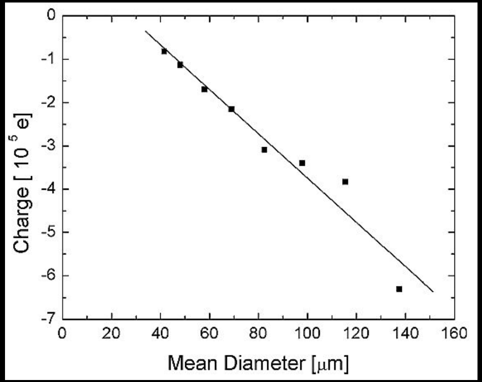
Electric forces become more relevant in low *g*

Earth: van der Waals / charging are significant only for fine powders (<10 mm)

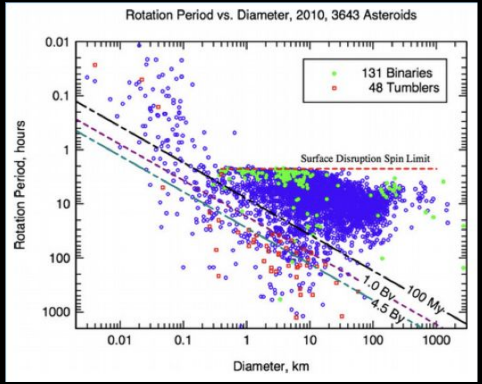
Moon: electric-levitated dust and regolith adhesion due to van der Waals forces are significant effects
Walton "Adhesion of Lunar Dust" (NASA/CR—2007-214685)



Asteroids: van der Waals forces are enough to provide non-negligible tensile strength(~10 kPa ~ tomato)



Earth-based experiments on regolith simulant
Sternovsky, Robertson, Sickafoose, Colwell, Horányi. *JGR Planets* (2002)

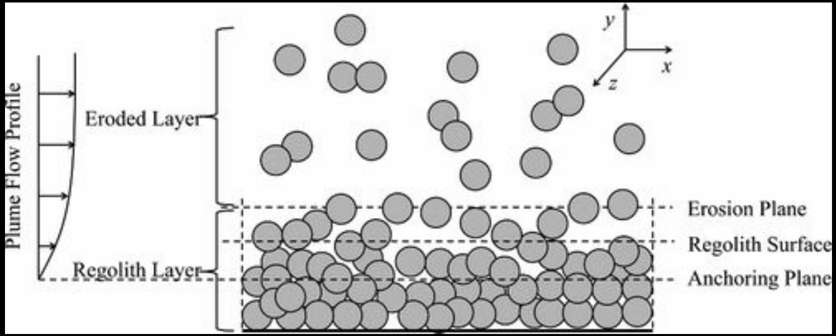


Simulations of asteroid rotation rates act probe tensile strength
Sánchez & Scheeres. Meteoritics & Planetary Science (2014

Still more open questions ...

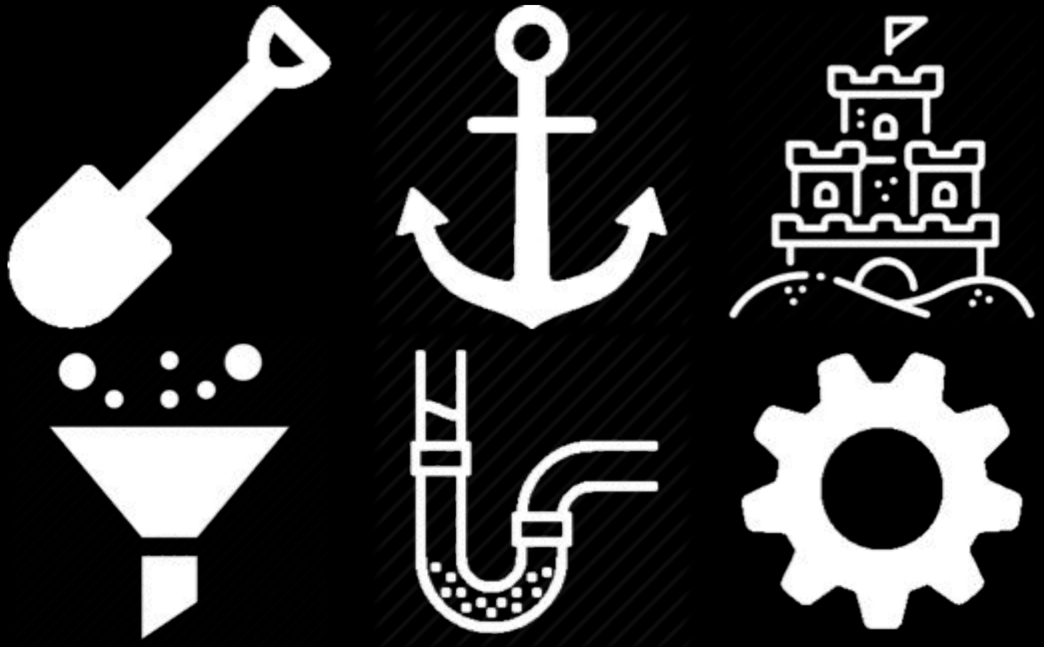
- **Granular segregation** ➛ size/density/shape sorting
- **Granular gases** ➛ safety of launch and landing sites, erosion
- **Stability of soils** ➛ building permanent structures (power, living)
- **Drag on an intruder** ➛ digging, anchoring, locomotion

Wilkinson, Behringer, Jenkins, Louge. *AIP Conference Proceedings* (2005)
Berger et al. *Phys. Rev. E.* (2013)
Kokelaar et al. *JGR Planets* (2017)
Shrivastava et al. *Science Robotics* (2020)
Ruppert, Ross, Vlassak, Elvis. (2021)



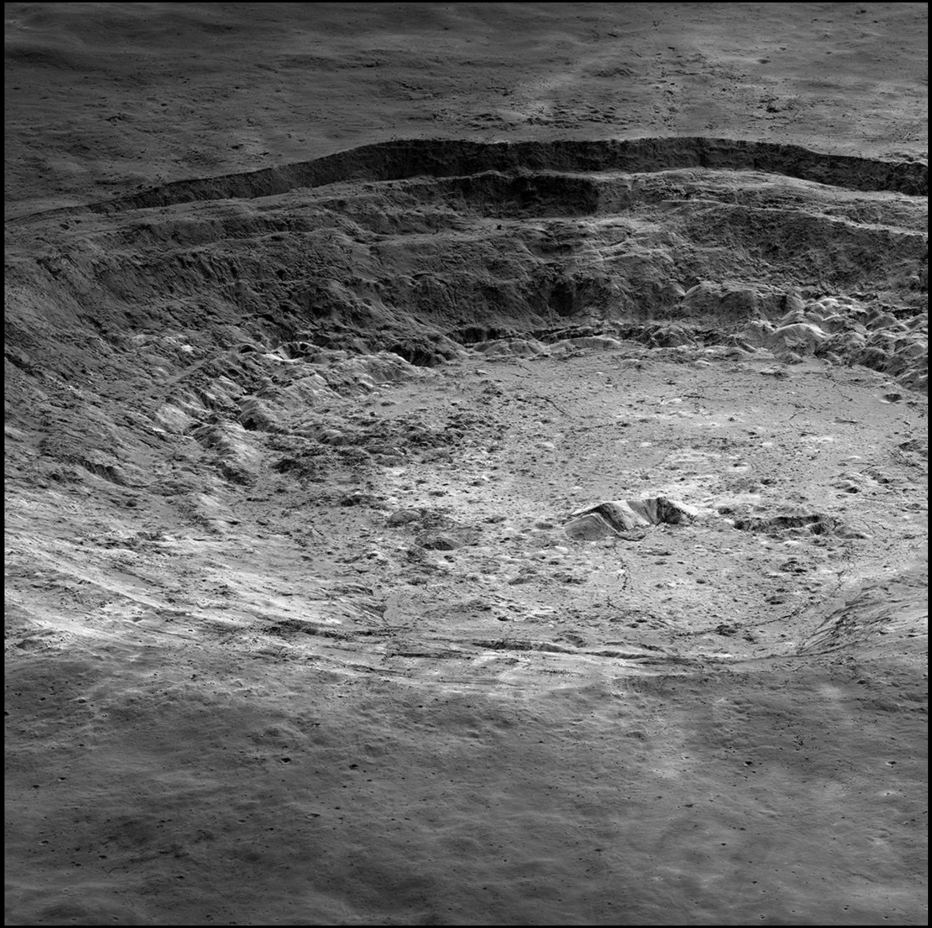
Exploration & in-situ resource utilization

- Lunar activities depend on sound knowledge of granular dynamics



Self-portrait of the rover Spirit stuck in a Martian sand trap (2009)
NASA/JPL-CALTECH

Geomorphology on the Moon

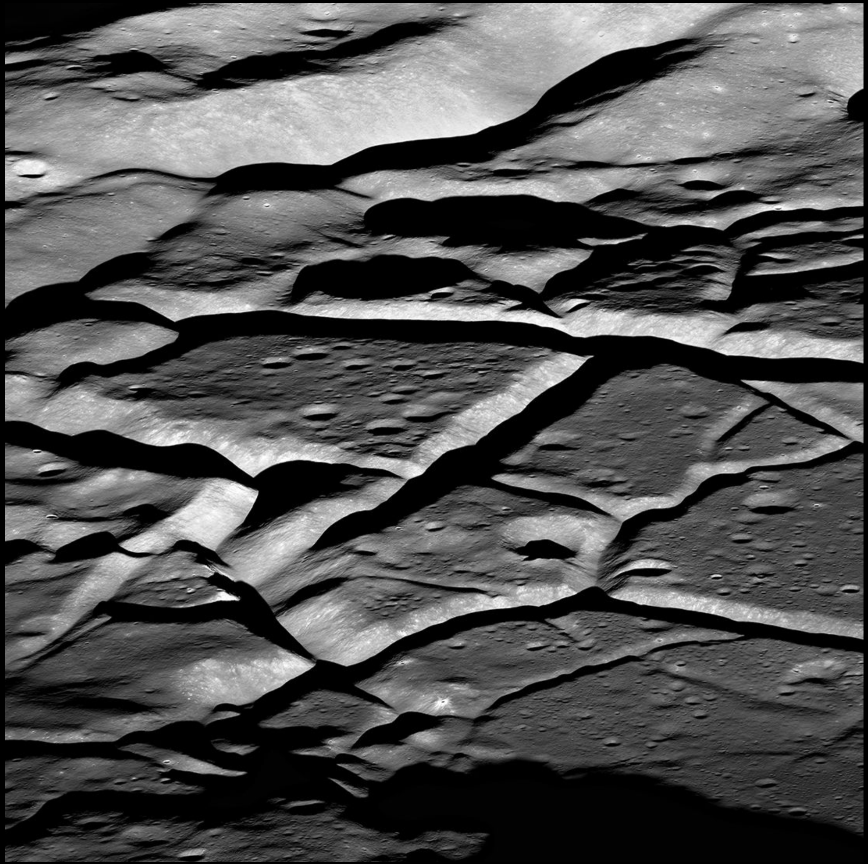


- Understand how the landscape formed
- Make comparisons with geological features on other planetary bodies
- Requires sound knowledge of granular dynamics

NASA/GSFC/Arizona State University

Aristarchus crater

Geomorphology on the Moon



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NASA/GSFC/Arizona State University

Komarov crater: fractured magma

Advantages of lunar-based experiments

- Automated experiments sent as payloads
  - Time to do slow experiments & many repeated trials leads to better science outcomes
  - Most experiments can operate outside of habitats
- Ready availability of real lunar regolith (eventually)
- Replace numerical simulations with actual data
- Replace approximation of lunar environment, beyond just low-*g*, with real vacuum & radiation

- Ability to collaborate internationally with partners abroad to explore and understand the laws of physics and our solar system

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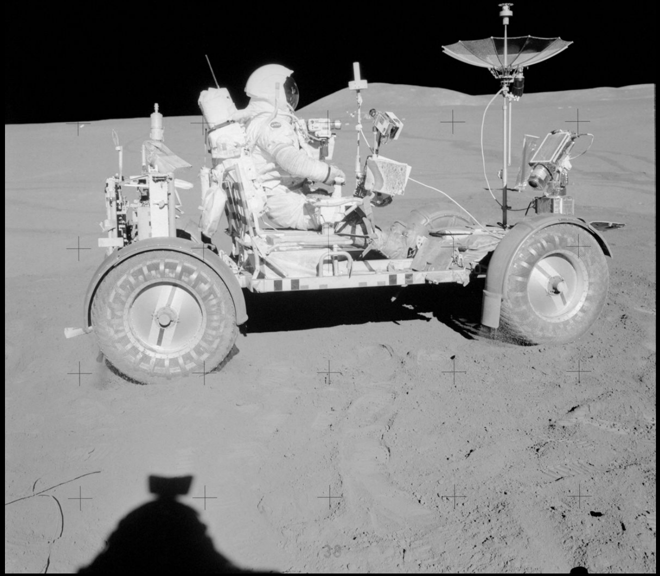

NASA/JSC (1971)