A Comprehensive Study of Planetary And Terrestrial Rover Development

Production-level and College-level Rovers

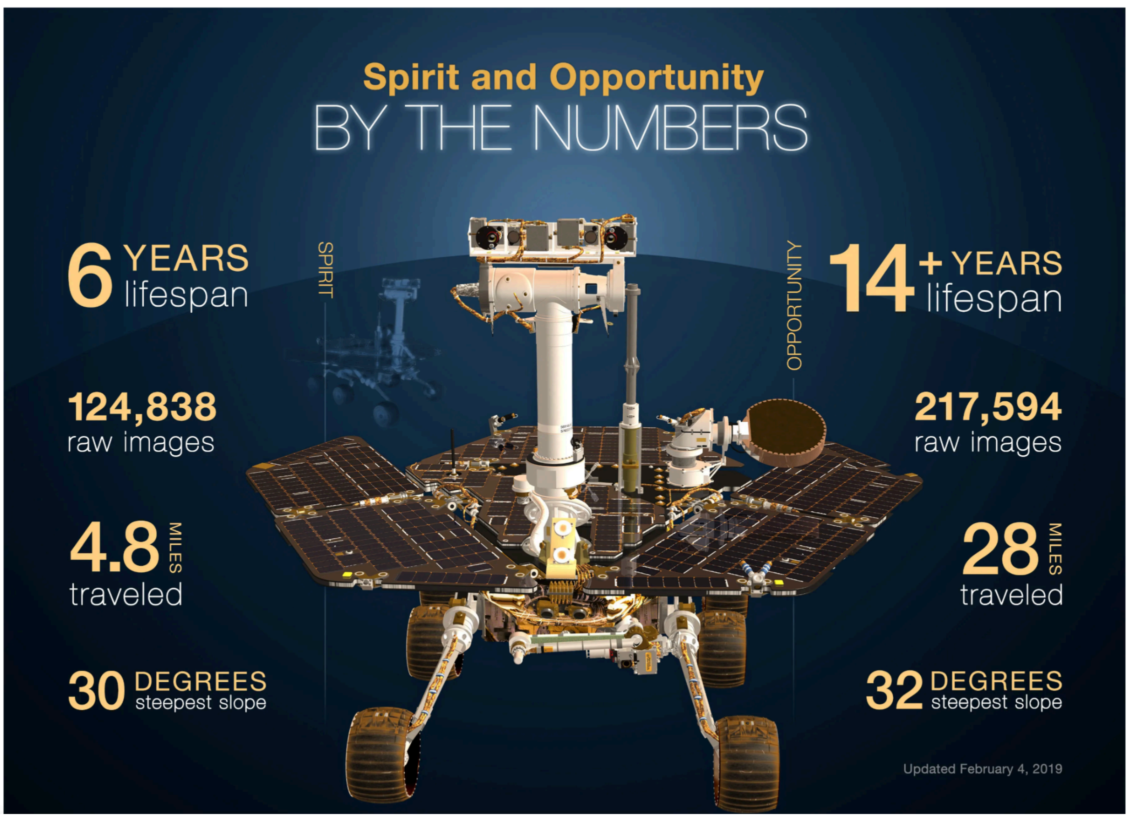
Prachi Choubey, 2025
Research & Development Team
Society for Aerospace and Space Technology (SAST)
Rishihood University

Contents

1. Abstract

This paper presents a comprehensive study of planetary and terrestrial rover development, examining both production-level rovers from major agencies and corporations as well as college-level rovers developed in the past few decades. This study aims to study various key systems, design, engineering and innovation of each relevant rover that contributes to its mission and performance success.

A structural framework was applied to incorporate a technical timeline of research and development for each rover mission selected, basic & contextual background information, technical specifications, paylodes[1], mission objectives and cost ranges. In addition to this, it also includes a case study of one of the more relevant and technologically interesting rovers that has the potential to influence and inspire the next generation of amateur rover development and possibly college and production-level rover development as well.



Credits: NASA/JPL-Caltech, Infographic depicting the Mars Exploration Rovers (MER) Spirit and Opportunity

2. Introduction

A planetary rover is an automated robot designed for planetary surface exploration under harsh extraterrestrial climates and terrains. Typically, a planetary rover is tasked with a certain objective and uses technology like machine learning to navigate the landscape around itself, with the use of navigation technologies like AutoNav[2] and eNav[3][10]. These rovers represent the pinnacle of human engineering and scientific capabilities and map a clear structural advancement in human knowledge and skills. Understanding the evolution of such capable machines therefore, becomes essential for any research and development initiatives that aim to replicate and innovate one such robot for scientific research and extraterrestrial exploration. This paper hence, aims to study the historical evolution and advancement of planetary rovers built and improved over the past decades on functional variables like mobility, power, autonomy, communication, navigation, and scientific payloads integrated into them.

3. Prior Work

3.1 Timeline of Major Rover Development

1970: Lunokhod 1 Rover (USSR)

- Launched by the Soviet Union on November 10, 1970, aboard the Luna 17 spacecraft to the Moon
- It was the first rover ever to touch the surface of an extraterrestrial body, landing in the Sea of Rain region of the Moon on 17th November.

1997: Sojourner Rover (NASA)

- The Mars Pathfinder, a robotic spacecraft, was launched with the Sojourner in 1996.
- Sojourner became the first roving probe[4] to reach the Martian surface on 4th July 1997, landing in the Chryse Planitia region of Mars.

2004: Spirit & Opportunity Rovers (NASA)

- Spirit and Opportunity were launched aboard two different Delta II rockets on June 10, 2003 and July 7, 2003, respectively, to the Martian surface.
- They were a part of NASA's Mars Exploration Rover (MER) mission.

2012: Curiosity Rover (NASA)

- In 2011, the Mars Science Laboratory mission successfully launched the Curiosity rover on the Martian Surface.
- The main objective is to search for evidence of life on the planet.

2019: Yutu-2 (CNSA)

- China National Space Administration (CNSA)'s Chang'e 4 spacecraft launched the Yutu-2 rover on the Lunar surface, becoming the first rover to ever touch the far side of the Moon in 2019.

2019: Pragyan-Chandrayaan-2 Rover (ISRO)

- ISRO's second lunar mission, Chandrayaan-2, consisted of a moon orbiter, a lander[5] Vikram and a rover called Pragyan.
- It was destroyed in a crash-landing along with its lander, Vikram

2020: Perseverance Rover (NASA)

- The Mars Exploration Program (MEP) launched the Perseverance rover, Ingenuity helicopter and their payloads aboard the Atlas V spacecraft to the Martian surface.[1]

2023: SORA-Q, Hakuto-R Mission 1 Rover (JAXA)

- Takara Tomy, JAXA and Doshisha University made the rover to be launched with Hakuto-R to the moon, but it was destroyed in the lander crash in 2023

2023: Pragyan- Chandrayaan-3 (ISRO)

- The LVM-3 spacecraft launched the Chandrayaan-3 mission to the south pole of the moon for an in-situ chemical analysis of the lunar surface.

2024: The SLIM Rovers (JAXA)

- LEV 1 and LEV 2 are tiny rovers developed by JAXA[7] in cooperation with Tomy, Sony Group, and Doshisha University to be deployed on the Lunar surface as a part of the SLIM[8] lander.

- Lunar Excursion Vehicle 2 has the shape-changing mechanism developed for toys by TOMY and Doshisha University.
- Lev-2 has two cameras and a stabilizer used for navigation. It will transmit its data back to Earth through LEV-1

3.2 Technical Specifications, Cost Ranges and Payloads

Rovers	Mass	Power Source	Objective	Scientific payload	Key Innovations	Mission Cost
Perseverance (NASA)[1]	1,025 kg	MMRTG[6] (Nuclear)	Search for bio-signatures of ancient life Collect and cache rock samples for return to Earth Test technologies for future human missions	Mastcam-Z SuperCam (LIBS, Raman, microphones) PIXL (X-ray fluorescence spectrometer) SHERLOC (UV Raman spectrometer) MOXIE (oxygen generation experiment) RIMFAX (Ground-penetrating radar	Sample caching system for future Mars Sample Return missions AI-assisted autonomous navigation with reduced human intervention Integration of ground-penetrating radar with mobility operations Technology demonstration payloads for human exploration (MOXIE)	$2.7B
Curiosity (NASA)	899 kg	MMRTG (Nuclear)	Determine if Mars ever supported microbial life Study organic molecules and habitability Analyze Martian climate and radiation	SAM (Sample Analysis at Mars: gas chromatograph, mass spectrometer) CheMin (X-ray diffraction instrument) Mastcam ChemCam (laser-induced breakdown spectroscopy) RAD (Radiation Assessment Detector) DAN (Dynamic Albedo of Neutrons)	Nuclear-powered rover enabling continuous operation independent of sunlight First fully equipped mobile geochemistry laboratory on Mars Sky Crane landing system for precise rover deployment	$2.5B

Rovers	Mass	Power Source	Objective	Scientific payload	Key Innovations	Mission Cost
					Advanced autonomous navigation using visual odometry	
Lunokhod 1(USSR)	756 kg	Batteries charged by Solar Cell	Demonstrate remote-controlled surface mobility on the lunar surface. Study lunar soil mechanics and surface properties. Measure lunar radiation and temperature. Capture panoramic images of the lunar surface.	Television cameras (panoramic imaging) X-ray spectrometer (soil composition) Penetrometer (soil strength) Radiation detector Thermal sensors	First-ever remotely operated rover on an extraterrestrial surface An eight-wheel independent drive system enabling high redundancy Solar-powered daytime operation with battery-supported night survival Long-duration surface mobility far exceeding initial mission expectations	Not publicly disclosed
Yutu-2 (CNSA)	140 kg	Lithium-ion batteries charged by Solar panels	Explore the Moon's far side Study subsurface lunar structure Analyze surface composition and geology	Ground-Penetrating Radar (GPR) Visible and Near-Infrared Imaging Spectrometer Panoramic cameras Neutron and radiation detectors	First rover to explore the far side of the Moon Ground-penetrating radar for subsurface lunar analysis Lunar night survival strategy through power cycling and thermal design Long-duration lunar operation beyond initial mission timeline	Not publicly disclosed
Spirit (NASA)	185 kg	Lithium-ion (Li-ion) batteries	Search for evidence of past water activity on Mars Study Martian geology	Panoramic Camera (Pancam) Miniature Thermal Emission Spectrometer	Rocker–bogie suspension system enabling superior terrain traversal	$820M (MER program)

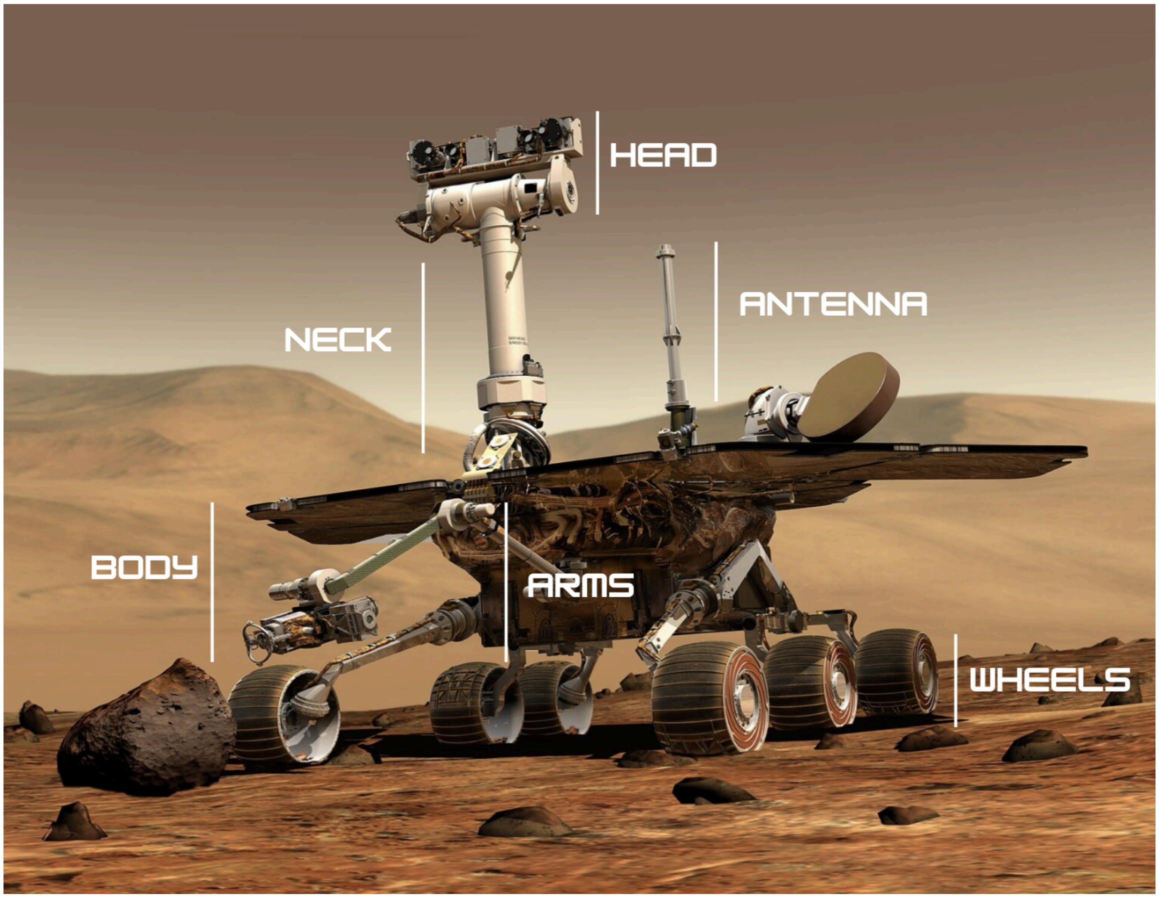
Rovers	Mass	Power Source	Objective	Scientific payload	Key Innovations	Mission Cost
			and climate history Characterize surface mineralogy	(Mini-TES) Mössbauer Spectrometer Alpha Particle X-Ray Spectrometer (APXS) Microscopic Imager Rock Abrasion Tool (RAT)	Long-term solar power optimization and dust-cleaning events High scientific output with relatively low mission cost Robust fault-tolerant software enabling multi-year operations	
Opportunity (NASA)	185 kg	Lithium-ion (Li-ion) batteries	Search for evidence of past water activity on Mars Study Martian geology and climate history Characterize surface mineralogy	Panoramic Camera (Pancam) Miniature Thermal Emission Spectrometer (Mini-TES) Mössbauer Spectrometer Alpha Particle X-Ray Spectrometer (APXS) Microscopic Imager Rock Abrasion Tool (RAT)	Rocker–bogie suspension system enabling superior terrain traversal Long-term solar power optimization and dust-cleaning events High scientific output with relatively low mission cost Robust fault-tolerant software enabling multi-year operations	$820M (MER program)
Sojourner (NASA)	10.6 kg	Non-rechargeable lithium-thionyl chloride ($LiSOCl_2$) batteries and solar panels.	Demonstrate the feasibility of mobile robotic exploration on Mars. Analyse the Martian rocks and soil. Test the autonomous navigation and hazard avoidance system.	Alpha Proton X-ray Spectrometer (APXS) Front and rear cameras Laser stripe projector (terrain profiling)	First mobile robotic exploration on Mars Autonomous hazard detection and basic path planning Airbag-assisted landing system	$265M (Mars Pathfinder)

Rovers	Mass	Power Source	Objective	Scientific payload	Key Innovations	Mission Cost
					enabling safe surface deployment Miniaturization of scientific instruments for mobile platforms	
SLIM LEV-1 (JAXA)	2.1- 3.1kg	Lithium-ion (Li-ion) batteries	Demonstrate precision lunar landing support Test micro-rover deployment and navigation Validate shape-changing rover technology	Camera, communication relay	Micro-rover deployment from a precision landing mission Shape-changing locomotion mechanism (LEV-2) Cooperative operation between multiple micro-rovers Data relay architecture between rover units	Not publicly disclosed $120 million[15]
SLIM LEV-2 (JAXA)	0.25 kg	Lithium-ion (Li-ion) batteries	Demonstrate precision lunar landing support Test micro-rover deployment and navigation Validate shape-changing rover technology	Dual cameras, stabilizer for navigation	Micro-rover deployment from a precision landing mission Shape-changing locomotion mechanism (LEV-2) Cooperative operation between multiple micro-rovers Data relay architecture between rover units	Not publicly disclosed $120 million[15]
SORA-Q, Hakuto-R M1 (JAXA)	0.25 kg	Lithium-ion (Li-ion) battery	Demonstrate ultra-small rover mobility on the Moon Test shape-changing	Miniature camera	Ultra-miniaturize d rover with shape-changing locomotion	Not publicly disclosed (Private mission)

Rovers	Mass	Power Source	Objective	Scientific payload	Key Innovations	Mission Cost
			mechanism for locomotion		Use of toy-industry mechanical innovation for space exploration Demonstrated feasibility of sub-kilogram lunar rovers	
Pragyan – Chandrayaan-3 (ISRO)	26-30 kg	Lithium-ion (Li-ion) battery	Perform in-situ chemical analysis near the lunar south pole Demonstrate rover mobility in extreme lunar conditions	APXS (Alpha Particle X-ray Spectrometer) LIBS (Laser-Induced Breakdown Spectroscope)	First successful rover operation near the lunar south pole Extremely cost-effective lunar rover design In-situ chemical analysis under extreme thermal conditions Demonstrated precision landing and surface mobility in challenging terrain	$75M
Pragyan – Chandrayaan-2 (ISRO)	26-30 kg	Lithium-ion (Li-ion) battery	Demonstrate rover mobility on the Moon Perform in-situ elemental analysis of lunar soil	APXS (Alpha Particle X-ray Spectrometer) LIBS (Laser-Induced Breakdown Spectroscope)	Lightweight rover optimized for low-cost lunar missions In-situ elemental analysis using compact spectrometers Demonstration of indigenous rover technologies	$140M
Michigan Mars Rover Team (MMRT) (URC)	45–50 kg	Lithium-ion (Li-ion) battery	Navigate autonomously in Mars-like terrain Perform scientific soil analysis tasks Execute manipulation	Soil sample collection system Spectrometer mock-ups (URC task-compliant) Temperature and	Modular arm design allowing quick repairs Strong integration of autonomy with	Not disclosed

4. Rover Engineering

4.1 Anatomy of A Rover



[*Credits: Artist's Rendition of the Opportunity Rover, Edited, NASA*]

Body	Made of aluminium alloys, often combined with titanium, steel alloys, and increasingly, carbon fibre composites to protect the sophisticated scientific instruments and equipment of the rover
Brain	Usually has two Rover Compute Element (RCE) that contain a radiation-hardened central processor like BAE RAD 750 in Perseverance that directly interfaces with rover instruments for memory, command and scientific data exchange.
Temperature control	Insulation and internal heaters keep the rover intact in extreme climates.

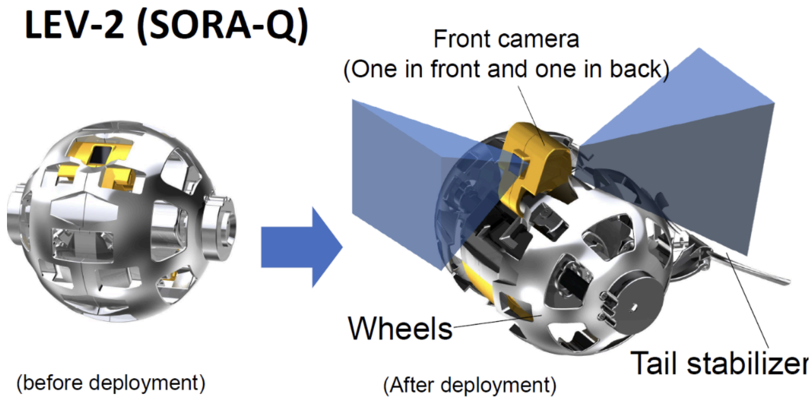
Neck and Head	A mast for the cameras to give the rover a human-scale view.
Eyes and other senses	Camera and instruments that provide the rover's RCE with information to aid navigation, communication, and scientific investigation.
Arms	The rover arms have three joints that provide flexibility to the rover for maneuvring scientific instruments to study the planet.
Wheels and legs	Made of aluminium, has cleats for traction and curved titanium spokes for springy support.
Energy	Usually use Li-ion batteries that get recharged with solar energy
Communication	The rovers have antennas to relay and receive information.

4.2 Case Study: LEV 2 - The SLIM Rovers (JAXA)

JAXA partnered with Sony, Doshisha University, and toy manufacturer TOMY Company (the company that made the Transformers toys) to develop LEV-2, the smallest lunar explorer rover in history, for photographing the success of the accompanying rover LEV-1 and the SLIM lander on the landing site. The rover is designed to separate, revealing a pair of cameras and a tail stabilizer. Rover can crawl across the lunar surface, swinging from side to side to move itself forward.[9]

[Credits: JAXA, LEV-2 in the crawling mode, swinging from side to side]

4.2.1 TOMY, the Transformers and LEV-2 Engineering



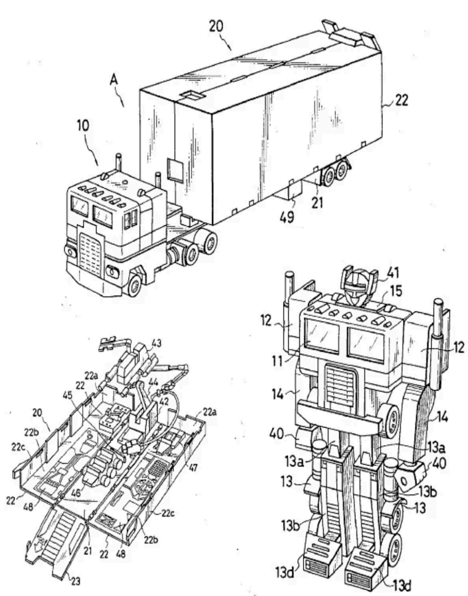
Size	Diameter approximately 80mm (3.1496 inch)
Weight	Mass approximately 228g
Camera	One camera in the front and one in the back, and one can capture images of the spacecraft and the surrounding environment.[8]

Credits: JAXA/TOMY/Sony Group Corporation/Doshisha University, LEV-2 "running form"

The rover is developed on the same technology that is used by TOMY Company in the development of the Transformer toys. LEV-2 is designed as a sphere, and only slightly heavier than a baseball. On the Lunar surface, it splits its outer shell into two hemispheres that function as wheels that aid its "crawling motion".

4.2.2 Relevant Transformers Technology and LEV-2

The Transformers toys use a precision mechanical engineering approach to design their toys that includes:



Complex Mechanical Joints	A dynamic system of joints, pins, and ratchets[9] that allows the parts to move and transform
Automorph Technology	Features a spring-loaded or gear-based system that allows automatic triggered motion of some part of the whole system on moving another.
Combiner Technology	Consists of multiple smaller "figures" designed with a certain joint mechanism that connects to one another to form a much larger robot
Microchips and Servo Motors	Allows for a fully automated, voice-controlled or app-controlled sequence of transformation in the robots[5]

Credits: Hiroyuki Obara, Wikimedia Commons

Discussion

This study highlights a consistent yet unique design and engineering choices that have contributed heavily to the success of each rover mission. It is evident that “out of the box” thinking has been the status quo for nearly every rover developed to best suit its limiting constraints. A great example of this is the LEV rovers of the SLIM mission, as well as both the Chandrayaan rovers. It presents us with a great opportunity to draw inspiration from these pioneering projects and, in doing so, learn as much as we can to aid our own aspirations for rover research and development efforts.

The case study of LEV-2 provides us with a blueprint for the use of unconventional technology and paves the way for a challenging yet satisfying effort on our part to develop something of similar calibre.

Conclusion

This study presented a comprehensive analysis of planetary and terrestrial rover development across production-level space missions and collegiate rover programs, intending to identify design principles relevant to future rover R&D. Out of all the rover subjects studied, LEV rovers proved the most relevant to our future endeavours. This paper tends to provide a foundational introduction as well as a platform for future research and development initiatives.

Appendix

1. *Payloads*: refers to the useful, intended cargo or data carried by a vehicle (like a rocket, plane, or ship) or system (like a computer network), excluding the parts needed for operation, such as the actual message in data, scientific instruments in a satellite, or passengers/goods on a flight, and in computing, it's the core data or malicious code within a transmission
2. *AutoNav*: Auto Nav (Autonomous Navigation) refers to systems allowing vehicles (cars, drones, spacecraft, robots) to navigate, plan paths, and move without human control, using sensors and AI
3. *eNav*: eNav stands for Enhanced AutoNav, an algorithm-and-software combination used on the Perseverance rover for more precise hazard detection and autonomous path planning on Mars. This system allows the rover to "think while driving" and avoid obstacles without continuous input from Earth.
4. *Probe*: an unmanned spacecraft carrying scientific instruments, launched by a powerful rocket, designed to explore distant planets, moons, or other celestial bodies, gathering data
5. *Lander*: a specialized spacecraft designed to detach from its main carrier rocket, travel to a celestial body (Moon, Mars, etc.), and perform a soft, controlled landing on the surface, remaining functional to conduct science or deploy rovers, unlike impact probes.
6. *MMRTG*: Multi-Mission Radioisotope Thermoelectric Generator. A nuclear battery that uses heat from plutonium-238 decay to generate reliable, long-term electricity and heat for deep space or planetary surface missions, powering rovers like NASA's Curiosity and Perseverance
7. *JAXA*: Japan Aerospace Exploration Agency
8. *SLIM*: Smart Lander for Investigating Moon
9. *Ratchets*: A mechanism used in toys that produces a clicking sound a provide with stable locking position for parts that are in need of temporary alignment together.

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