Rovers

MAE 4160, 4161, 5160

V. Hunter Adams, PhD

14 years, 46 days
28.06 miles (45.16 km)
“My batteries are low, and it’s getting dark.”

Today's topics:

- Methods for mobility
- Articulated wheel rovers
- Rolling mobility
- Stopping distance
- Swerving distance
- Power for mobility/ computation
- Sensor resolution
- Thermal management
- Case study

Methods for mobility

Wheels

- unicycle
- bicycle
- tricycle
- four wheels
- six wheels
- >6 wheels

Tracks

- segmented tracks
- elastomeric loops

Legs

- bipeds
- quadrupeds
- hexapods
- >6 legs
- wheels on legs
- hoppers
- hoppers with wheels
- grappling hooks
- other surface traction hybrids

Mobility without surface traction

- ground effect machines
- fixed wing aircraft
- rotary wing aircraft
- rockets/jets
- rocket/glider hybrid
- other free-flying hybrids

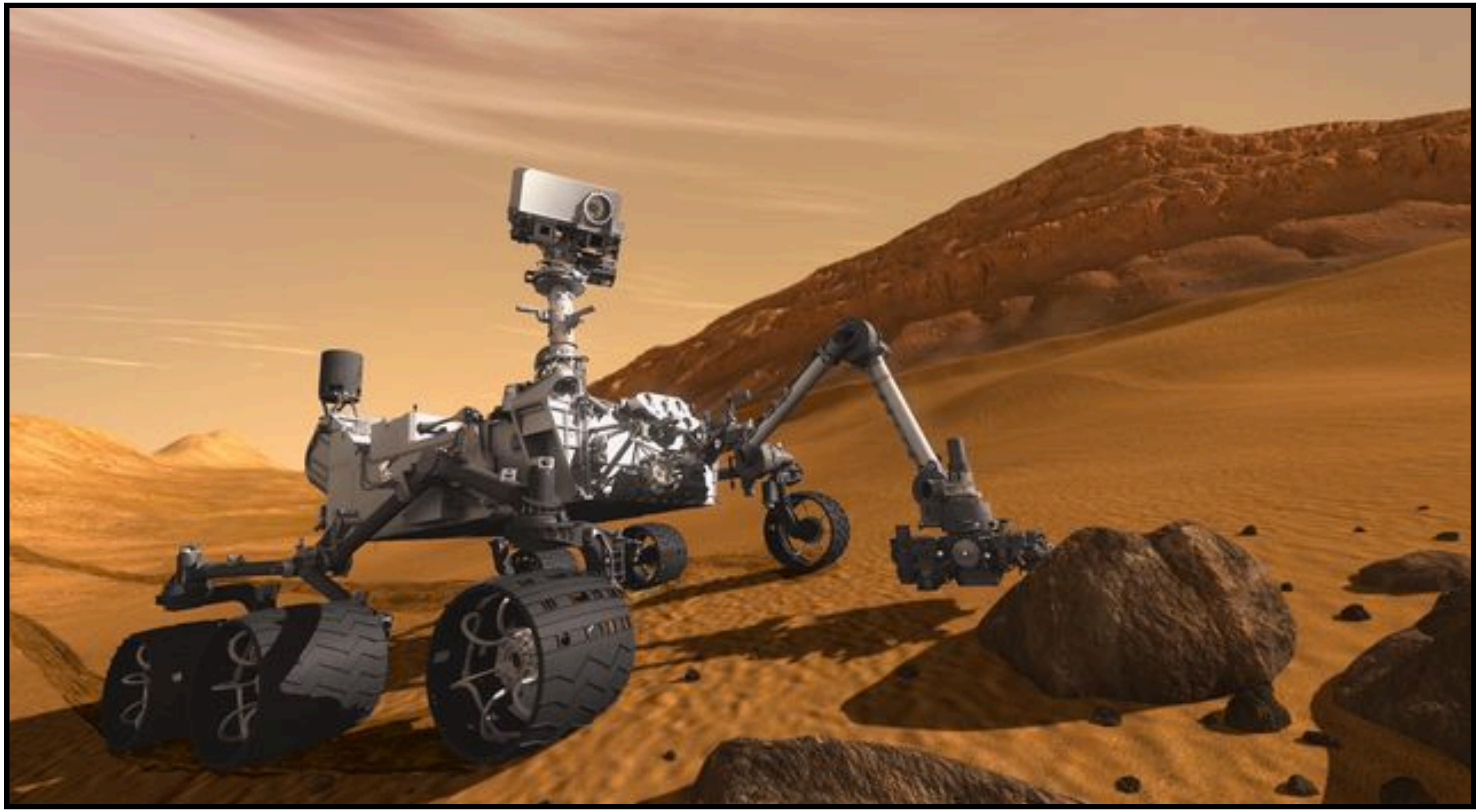
Methods for mobility

Wheels

- unicy
- bicyc
- tricyc
- four w
- six w
- >6 w

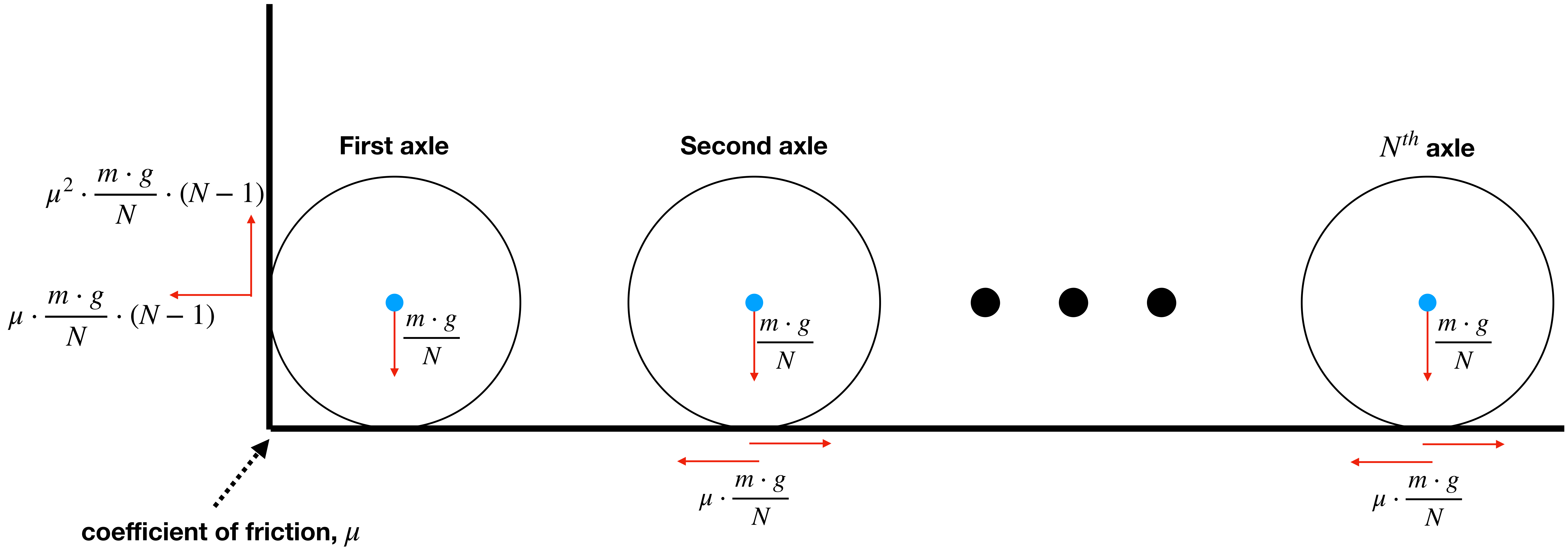
ction

Articulated wheeled vehicles

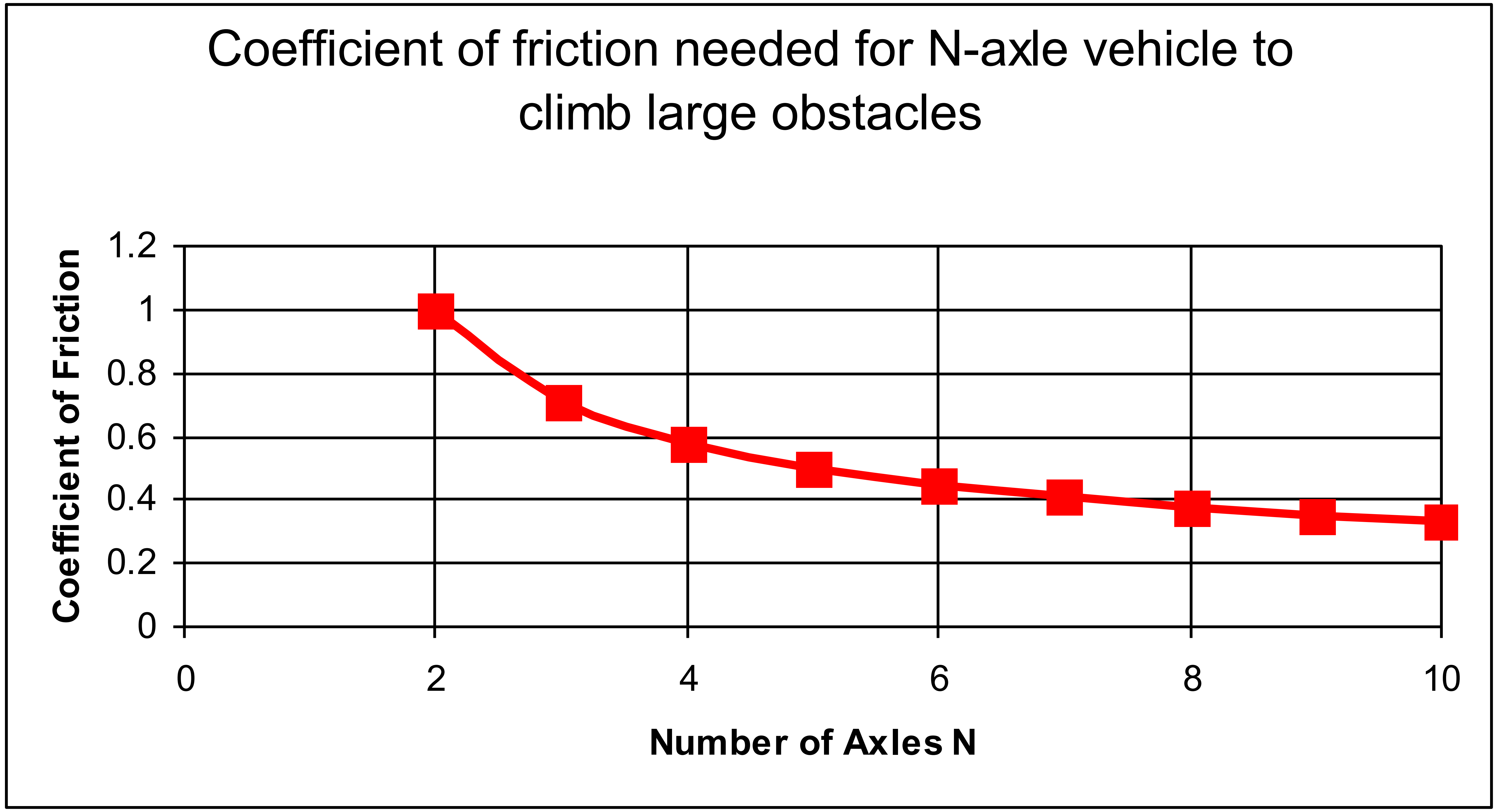


Articulated wheeled vehicles

- Articulated vehicle of mass m with N equally loaded axles
- Climbing of large (> wheel radius) obstacles occurs when thrust from $N-1$ trailing axles is enough to give friction lift equal to weight on first axle



Articulated wheeled vehicles

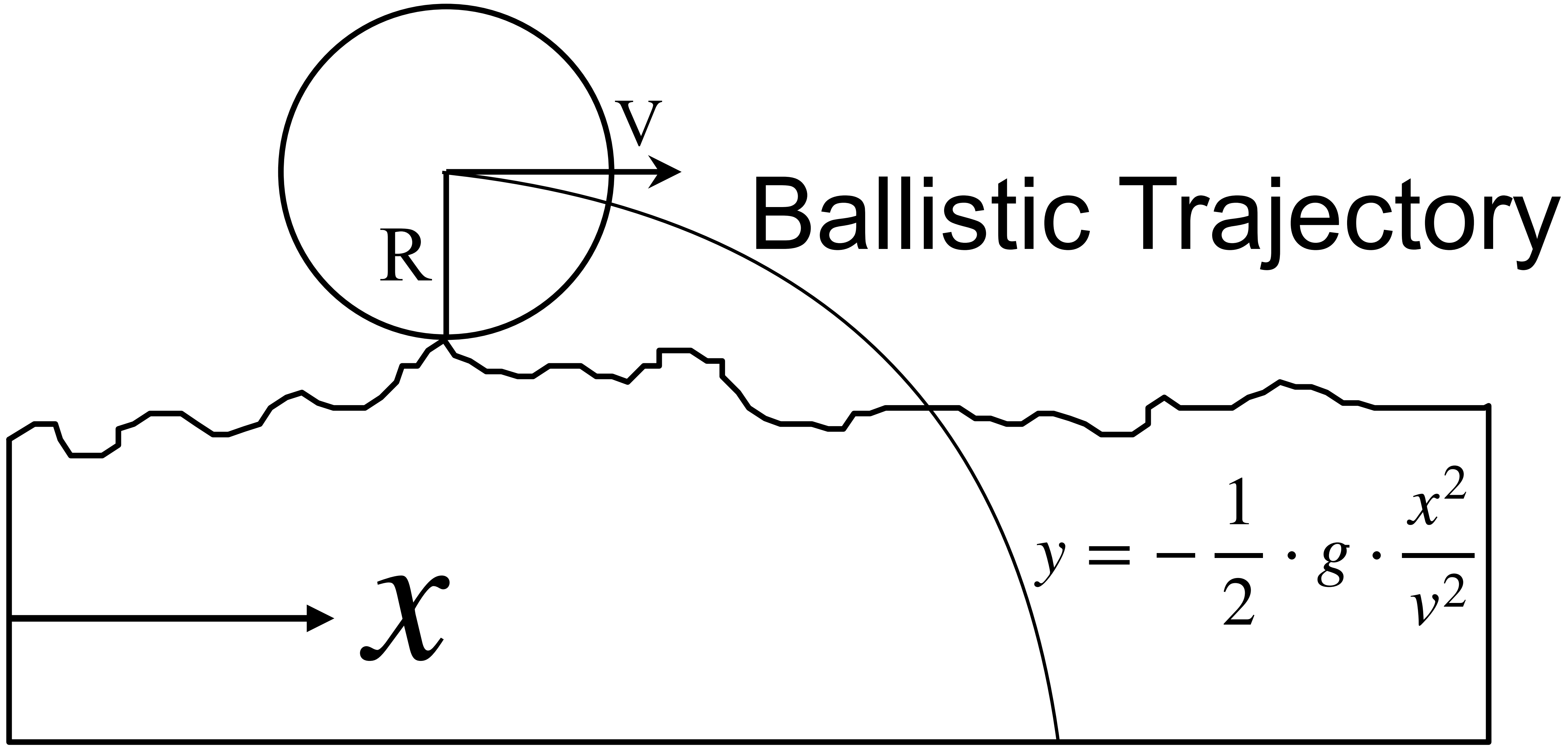


- >=3 axles are needed if friction coefficient is <~0.7, as found in natural terrain

Alternative: *don't equally load all axles*

- GoFor rover, developed '92-'93 at JPL
- Demonstrates center-of-gravity control
- Keeps 80% of weight over drive wheels, equivalent climbing performance to a 10-wheel articulated vehicle

Rolling mobility

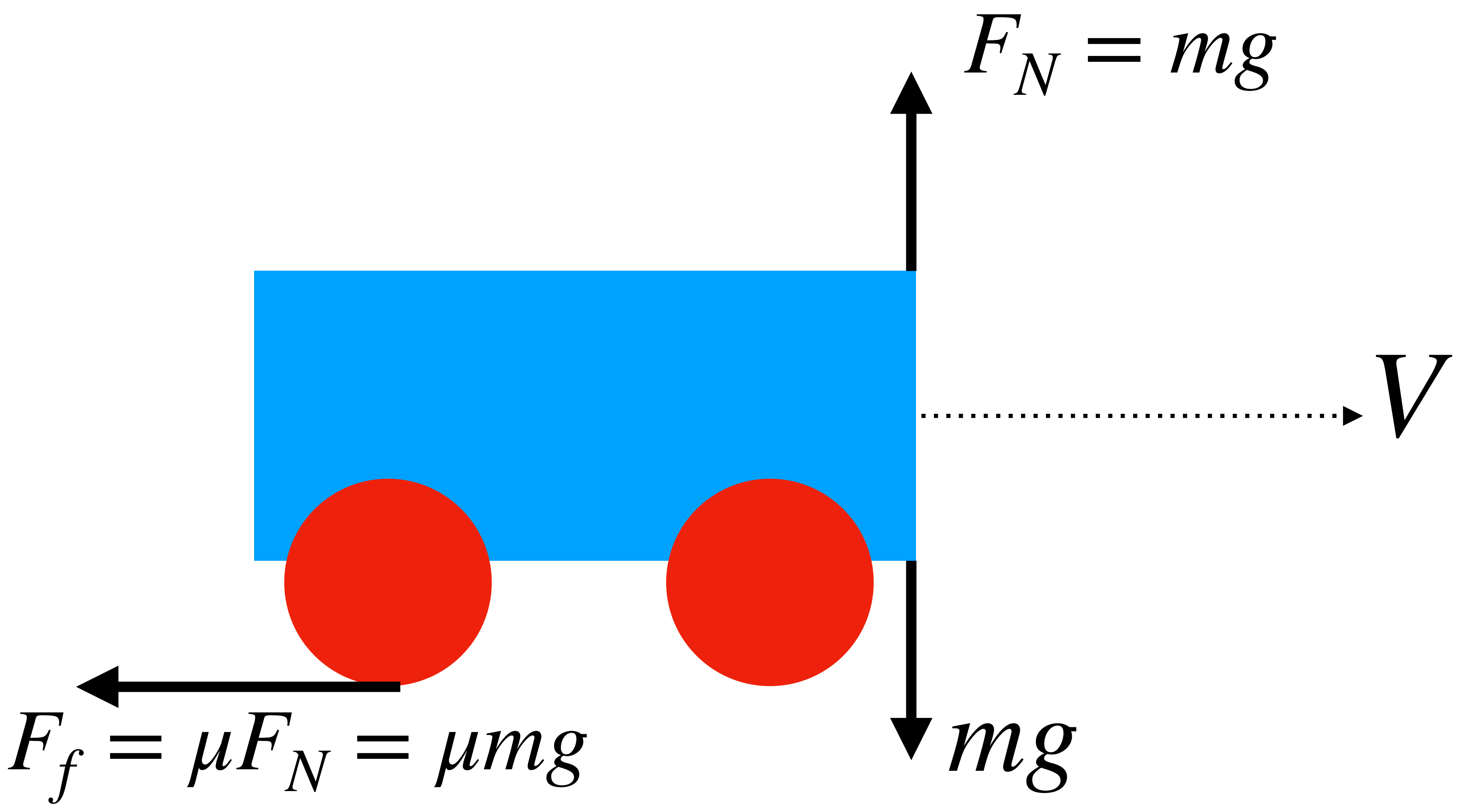


Assuming terrain without cliffs/holes:

- Slow rolling maintains surface contact
- When the tangent circle to a ballistic trajectory is larger than the wheel radius, the wheel loses surface contact
- For radius R, velocity V, and gravitational acceleration g, contact requires $V < \sqrt{R \cdot g}$
    - For $R = 0.05m$ and $g = 9.8m/s^2$, $V < 0.7m/s$
    - For $\frac{1}{6}^{th}$ g, $V < 0.28m/s$
    - For 10μg, $V < 2.2mm/s$

Curiosity rover: <4cm/s

Stopping distance



How far to stop?

Deceleration from braking:

$$F = ma \rightarrow \mu mg = ma \rightarrow a = \mu g$$

Time-independent acceleration equation:

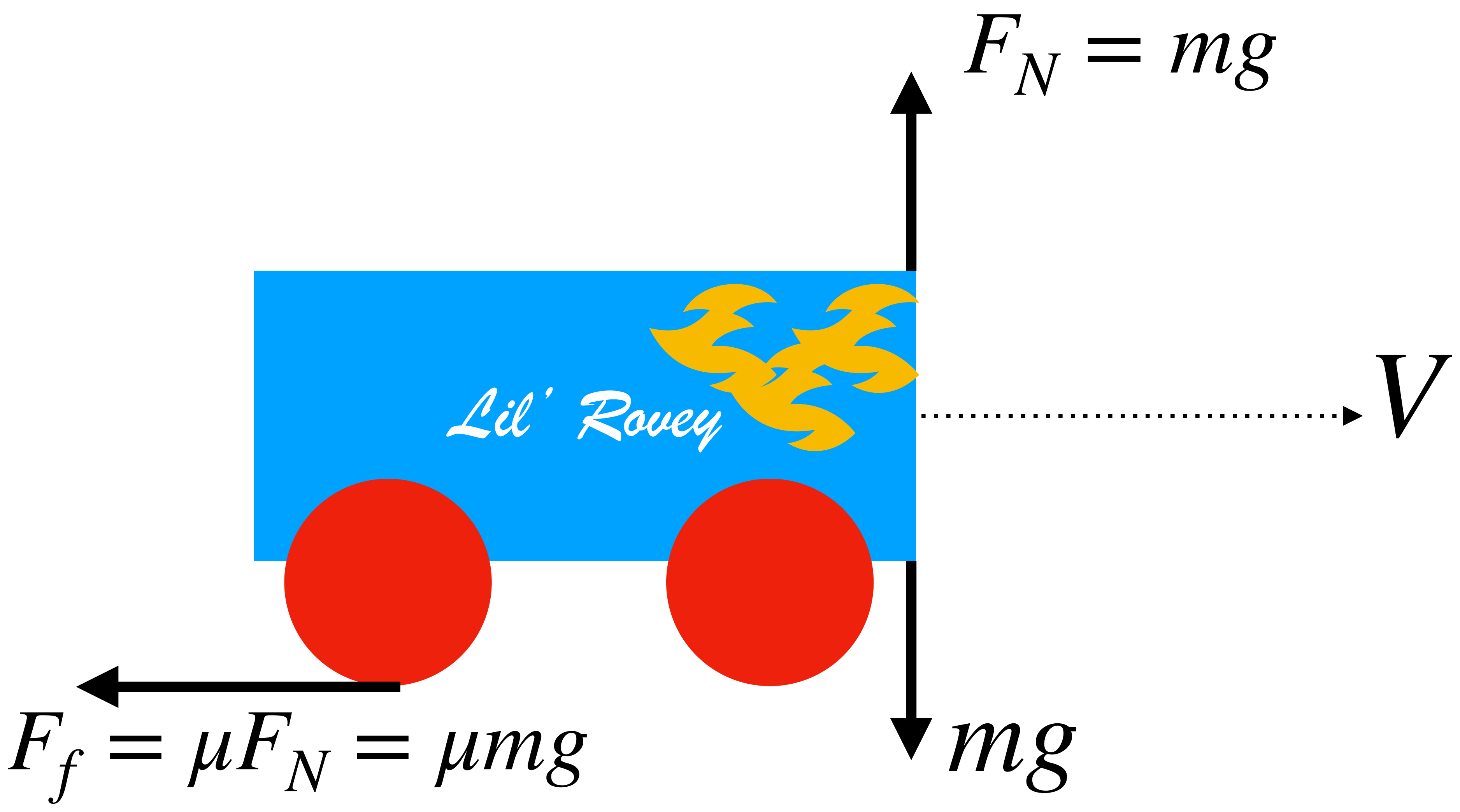
$$v_2^2 = v_1^2 - 2a\Delta x$$

Deceleration to stop $\longrightarrow v_2 = 0$. Thus:

$$\Delta x = \frac{V^2}{2\mu g}$$

For rubber on cement, $\mu \approx 0.7 - 0.8$
For sand, $\mu \approx 0.3$

Stopping distance



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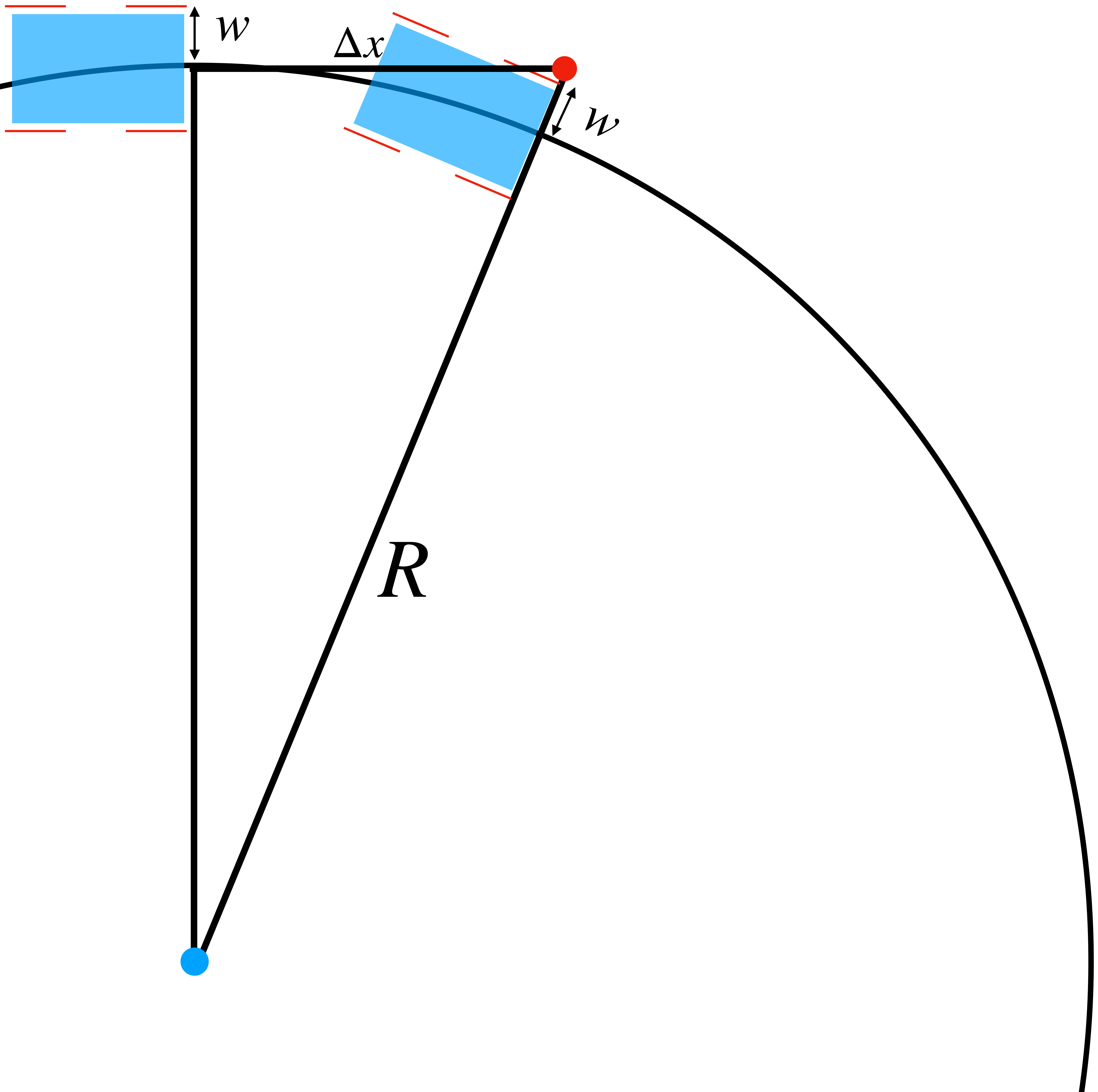
Swerving distance



Centripetal acceleration:

$$a_c = \frac{v^2}{R}$$

Substitute acceleration due to frictional force (previous slide):

$$\mu g = \frac{v^2}{R} \longrightarrow R = \frac{v^2}{\mu g}$$

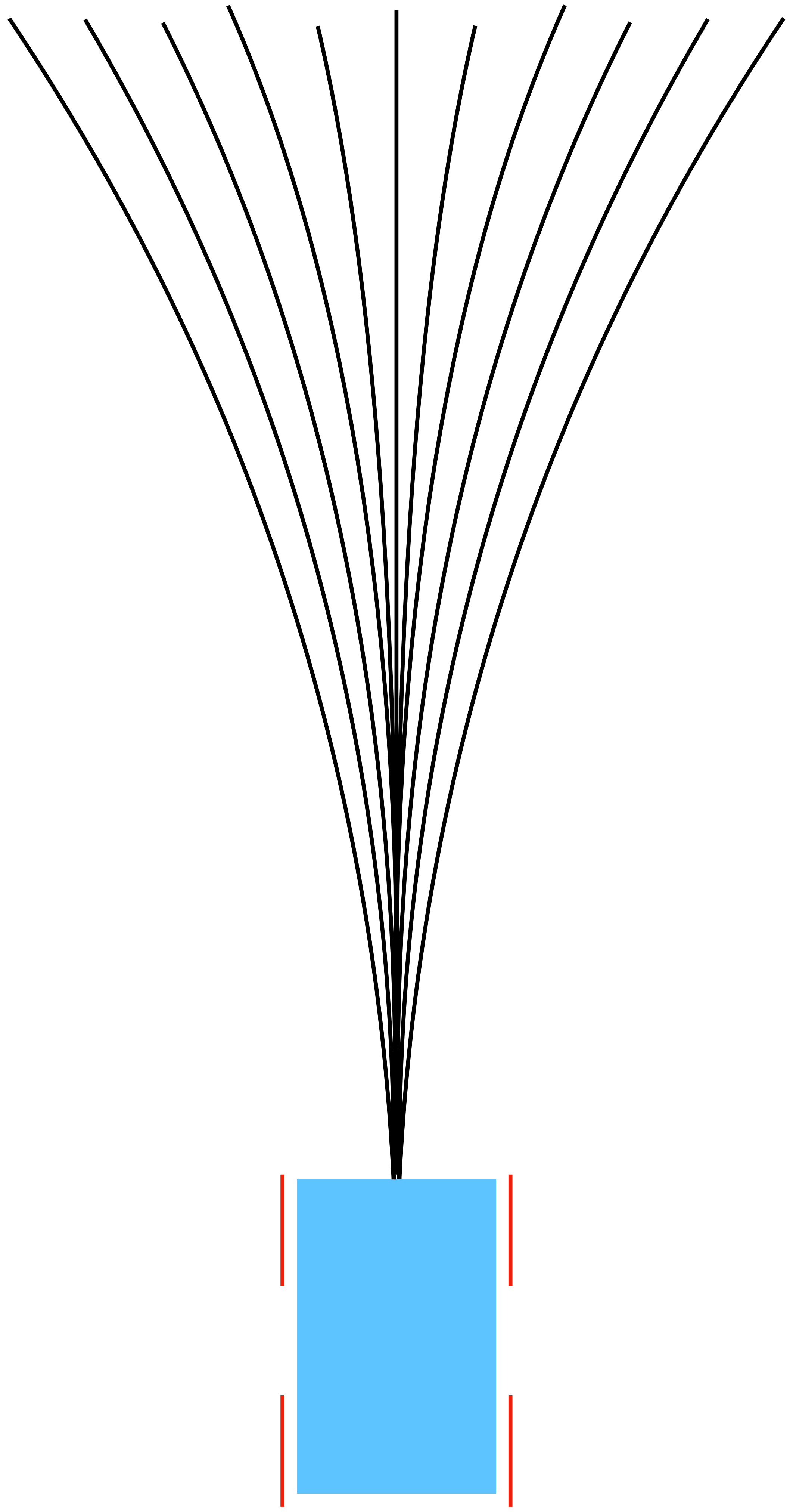
Apply geometry from the figure on the right:

$$R = \frac{\Delta x^2}{2w} - \frac{w}{2}$$

Substitute:

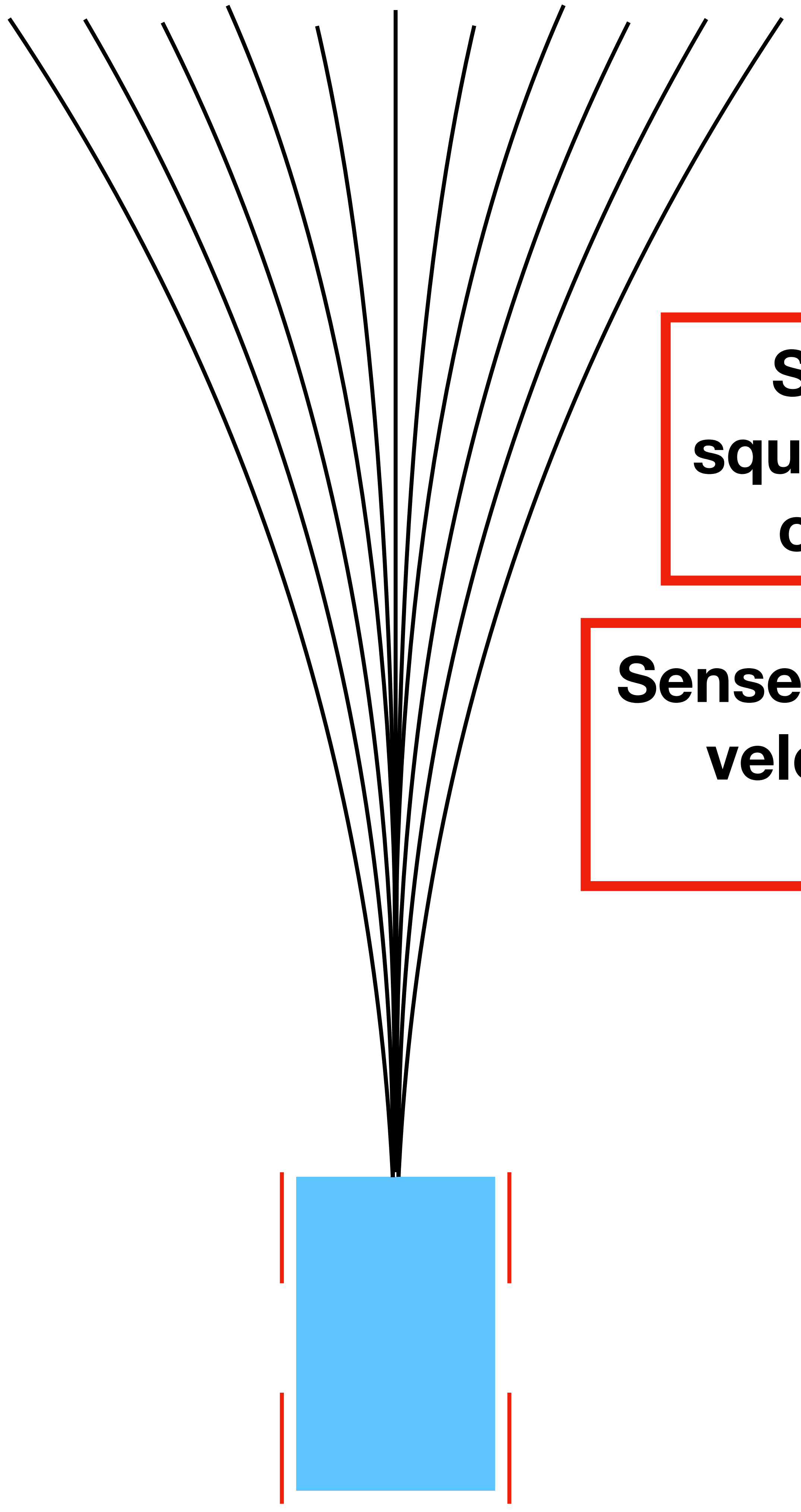
$$\Delta x = \left(\frac{2wv^2}{\mu g} + w^2 \right)^{\frac{1}{2}}$$

Sensing for dynamic mobility



- The rover must look ahead a distance of at least the stopping distance $\Delta x = \frac{V^2}{2\mu g}$ or the swerving distance $\Delta x = \left(\frac{2wv^2}{\mu g} + w^2\right)^{\frac{1}{2}}$
- Need to evaluate possible cross track arcs to limit of +/- maximum turning acceleration
- Ned to sense the terrain at the scale of a traction contact patch (typically ~w/5)

Sensing for dynamic mobility



Sensed points grow with square of velocity if measured out to stopping distance

Sensed points grow linearly with velocity if measured out to swerving distance

- The rover must look ahead a distance of at least the stopping distance $\Delta x = \dfrac{V^2}{2\mu g}$ or the swerving distance $\Delta x = \left(\dfrac{2wv^2}{\mu g} + w^2\right)^{\frac{1}{2}}$
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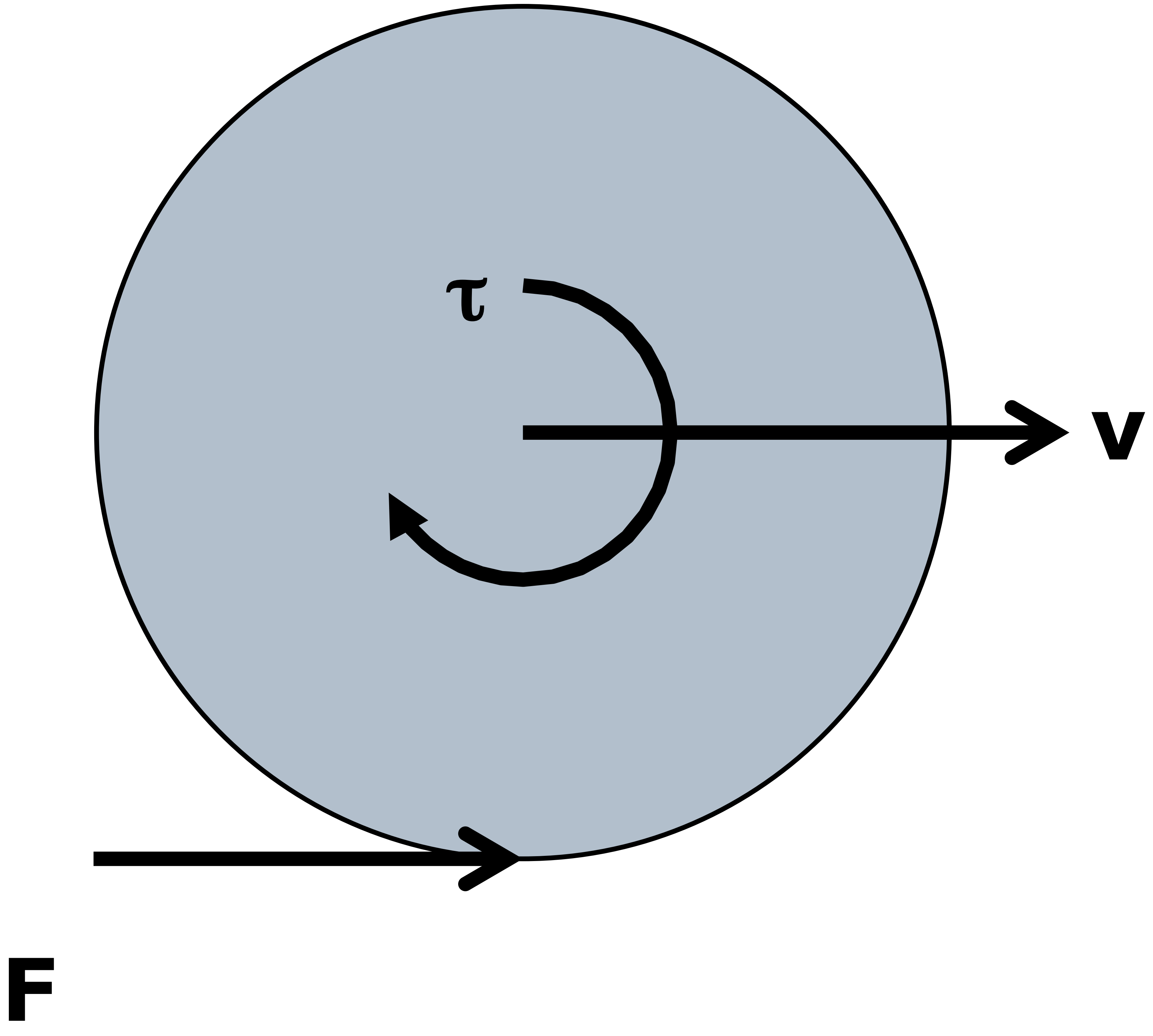
Rule of thumb . . .



- Every wheel of a rover must have a stall torque such that the rim thrust is at least half the weight of the vehicle in local gravity
- The mass of an actuator is the sum of the mass of the motor and the gearhead. Typical motors used in robotic vehicles have a mechanical power output of ~250W/kg, and optimized gearheads have an output torque of up to ~500Nm/kg, i.e. 2Nm/W (at zero speed)

Power for mobility

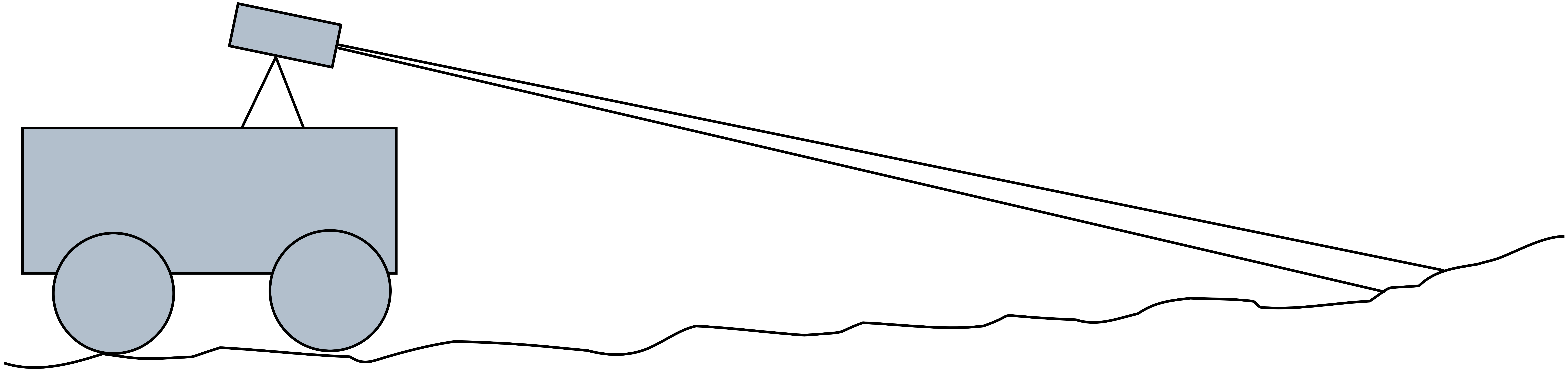
- Bus power for mobility $P = \mu m g v$, where μ is an "effective coefficient of friction," m is the vehicle mass, g is gravitational acceleration, and v is vehicle speed
- μ for a well-designed electric vehicle on a flat floor can be as low as 0.02
- μ for a wheeled vehicle on natural terrain is typically ≥ 0.08
- μ for a legged vehicle on rough terrain can be as high as 2 or more

Power for computation and mobility

- We assume that a certain number of computer instructions are required to evaluate terrain per meter of forward advance (or, more properly, per vehicle length of forward advance)
- Typically ~50MInstr/length for laser scanning and 500 MInstr/length for stereo vision
- Computers are ranked in MIPS/Watt (typically 100's or 1000's for commercial-off-the-shelf (COTS) processors, 1-50 for radiation-hardened flight processors)
- So **total power** is $P = \mu mgv + kv$ where:
  - k ~ 1W/(L/s) for COTS processors and up to 100 W/(L/s) for flight processors when $v = 1$ vehicle length per second (L/s) and $\mu mg \approx 3$m

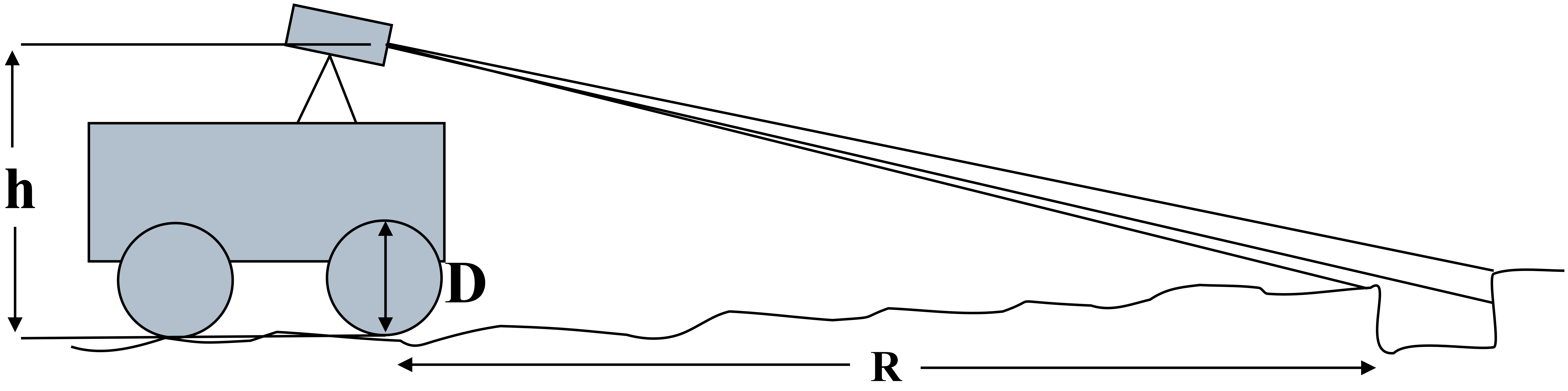
Sensor resolution

- Hazards are characterized by absolute elevation differences and slopes
- To distinguish a 1m traversable sandy slope (~20 deg) from a non-traversable slope (~30 deg) at 100 m stopping distance requires range accuracy of ~10 cm



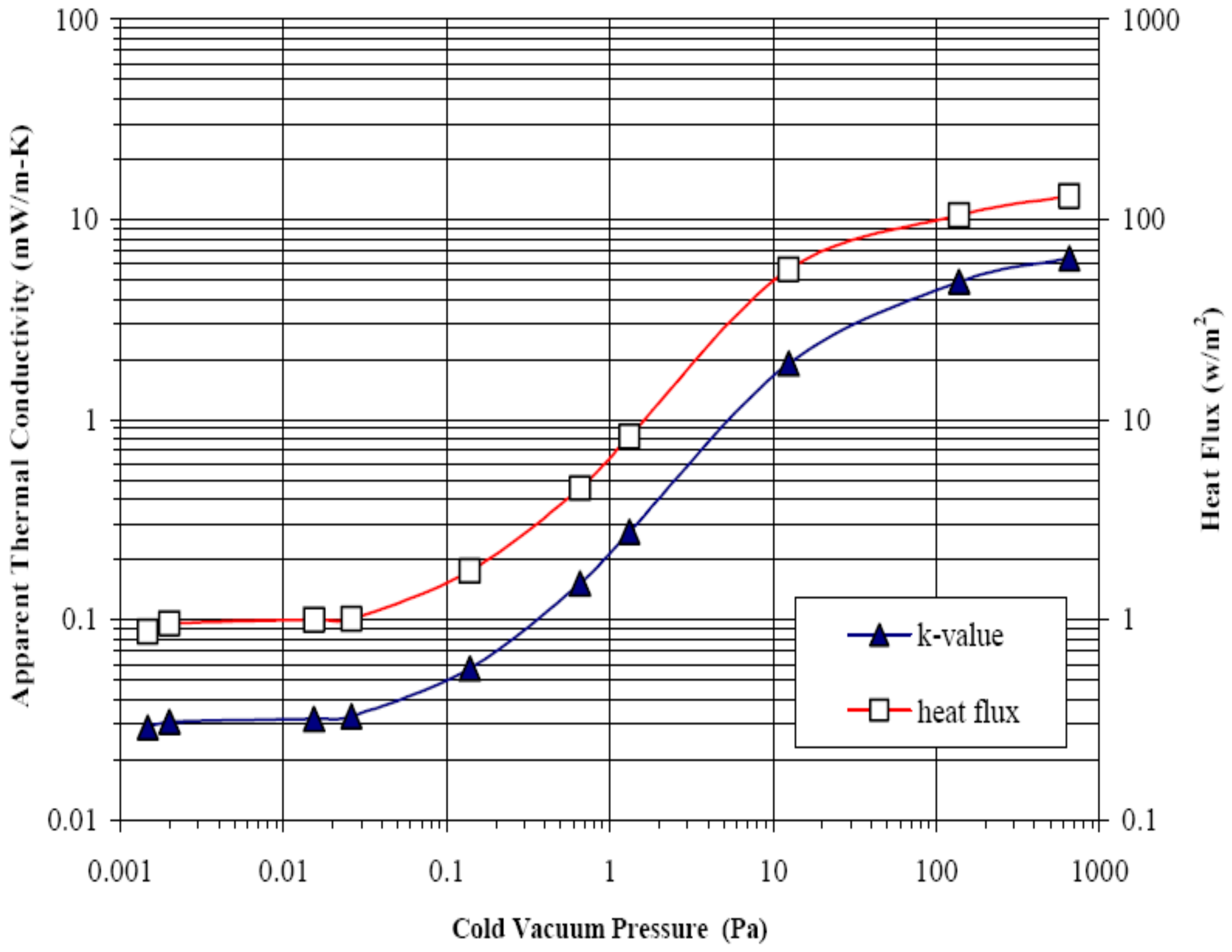
Negative obstacles

- Need to sense holes ~**D** wide and ~**D**/3 deep.
- Need to sense holes at the stopping/swerving distance. So, the faster you are going, the farther away the stopping/swerving distance, the higher your sensor must be.



Thermal control

- Multilayer Insulation (MLI) blankets offer superb insulation in hard vacuum (1W/m^2 or less heat leak)
- Mars atmosphere has too much pressure for MLI to work. Silica aerogel is somewhat better than common foam insulation
- Thermal range on moon and near-Earth objects (NEO's) is ~40-400K. Thermal range on Mars is ~180-300K.

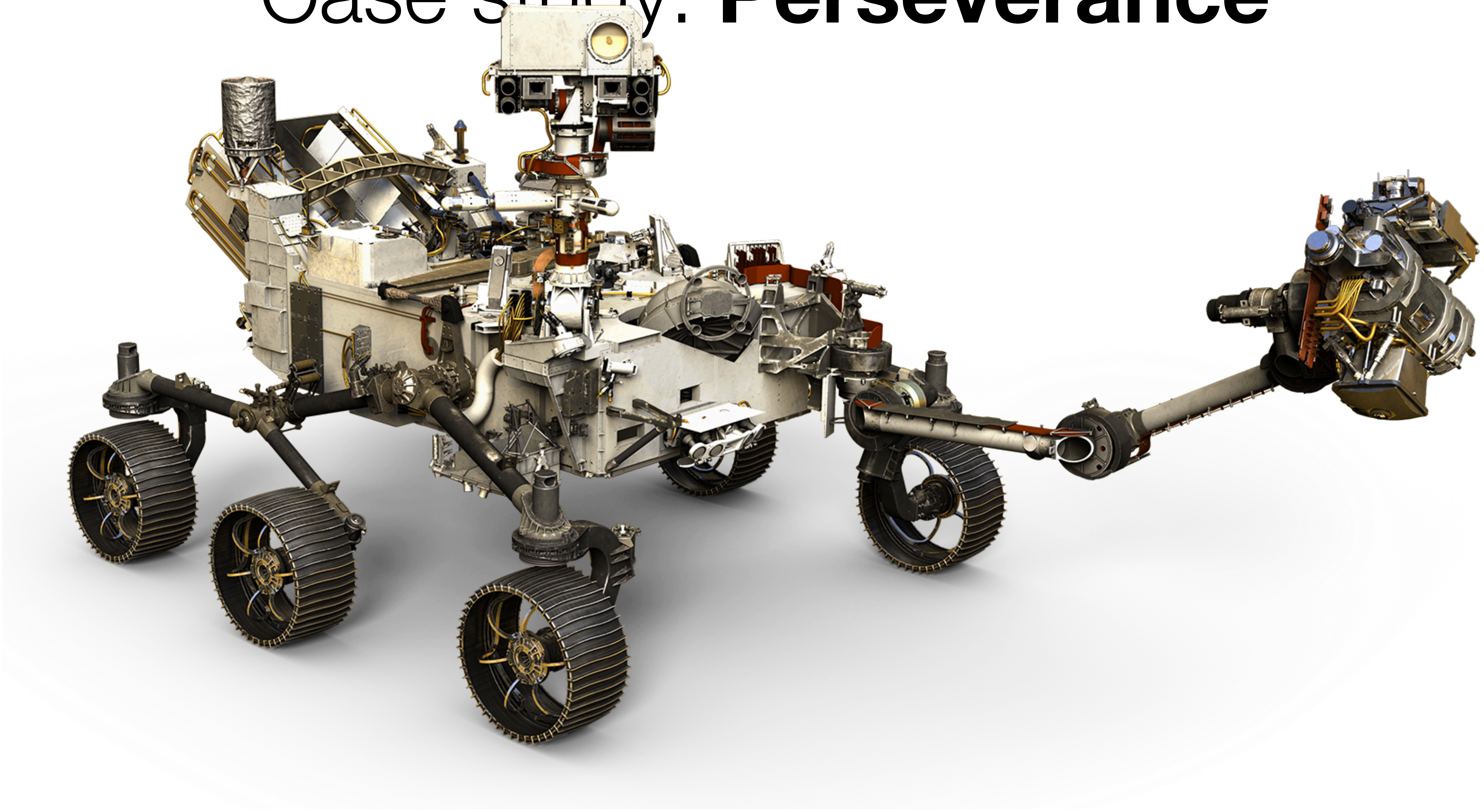


Fesmire, J. E., Augustynowicz S. D., Darve C., "Performance characterization of perforated multilayer insulation blankets," proc. 19th International Cryogenic Engineering Conference, ICEC 19, Narosa Publishing House, New Delhi, 2003, pp 843-846. Available at http://cdarve.web.cern.ch/cdarve/ Publications CD/ICEC19_MLI.pdf.

Approaches to thermal control

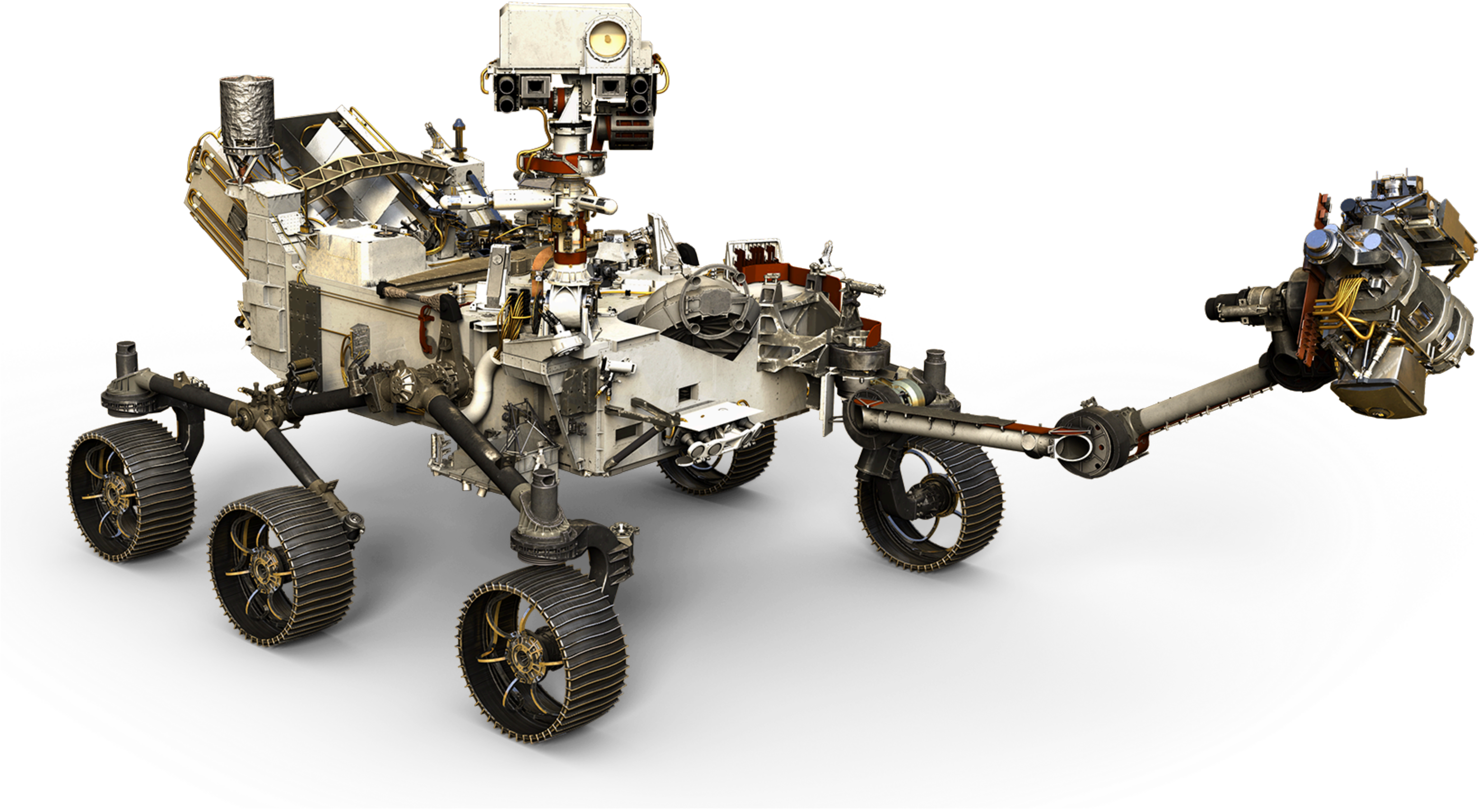
- Keep all sensitive items inside a “Warm Electronics Box” (WEB) and maintain within manufactures data-sheet thermal range. Limit number of wires to extremities; qualify selected sensors and actuator for extremity locations
- Supply heat (fluid loops, copper straps, or heaters) to extremities, insulate all external skin) - **similar to how birds keep their feet warm, countercurrent heat exchange**

Case study: **Perseverance**



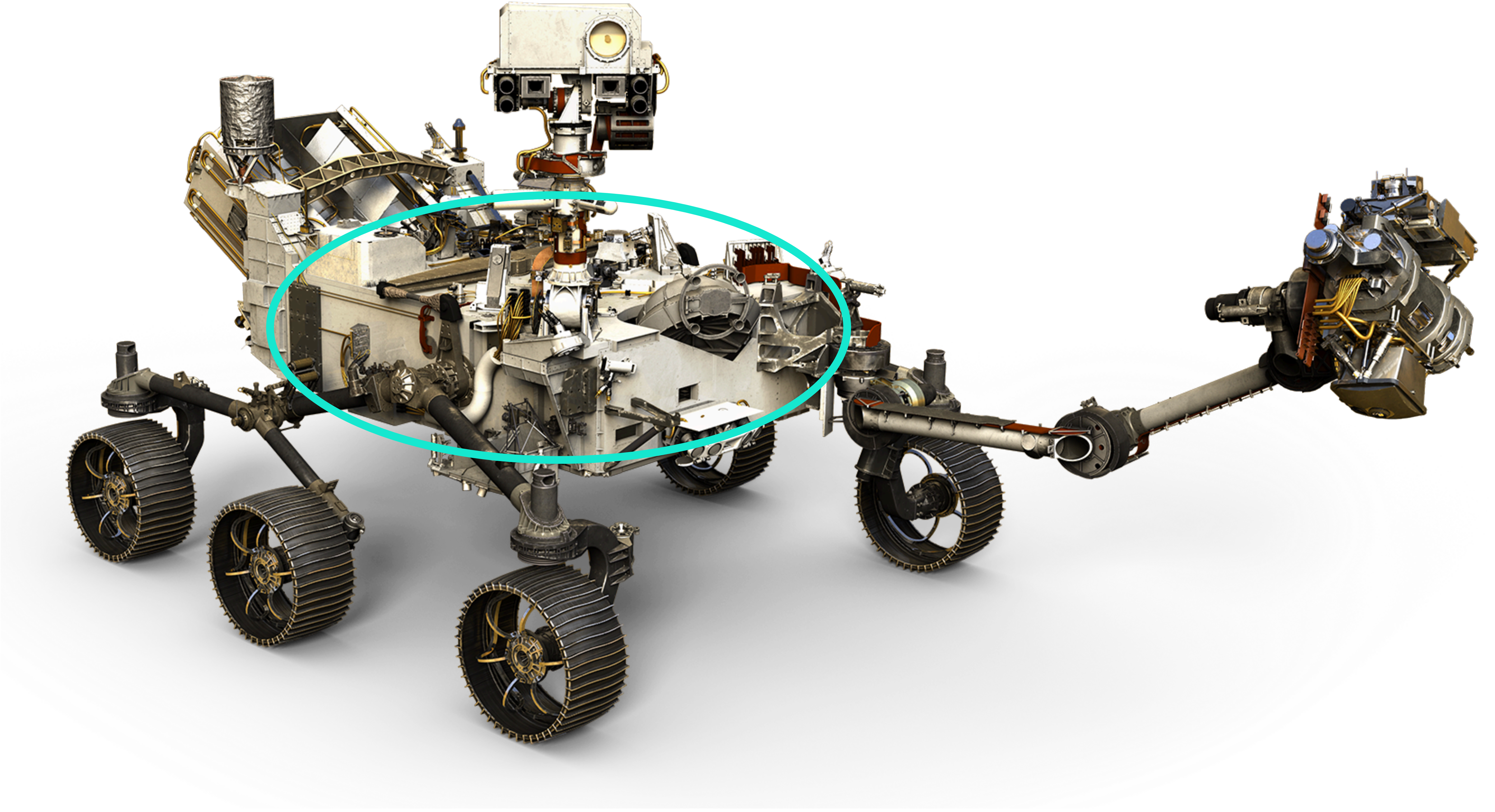
Mission

- Mission duration at least 1 Mars year (687 days)
- Goal 1: determine whether life ever arose on Mars
- Goal 2: characterize the climate of Mars
- Goal 3: characterize the geology of Mars
- Goal 4: prepare for human exploration



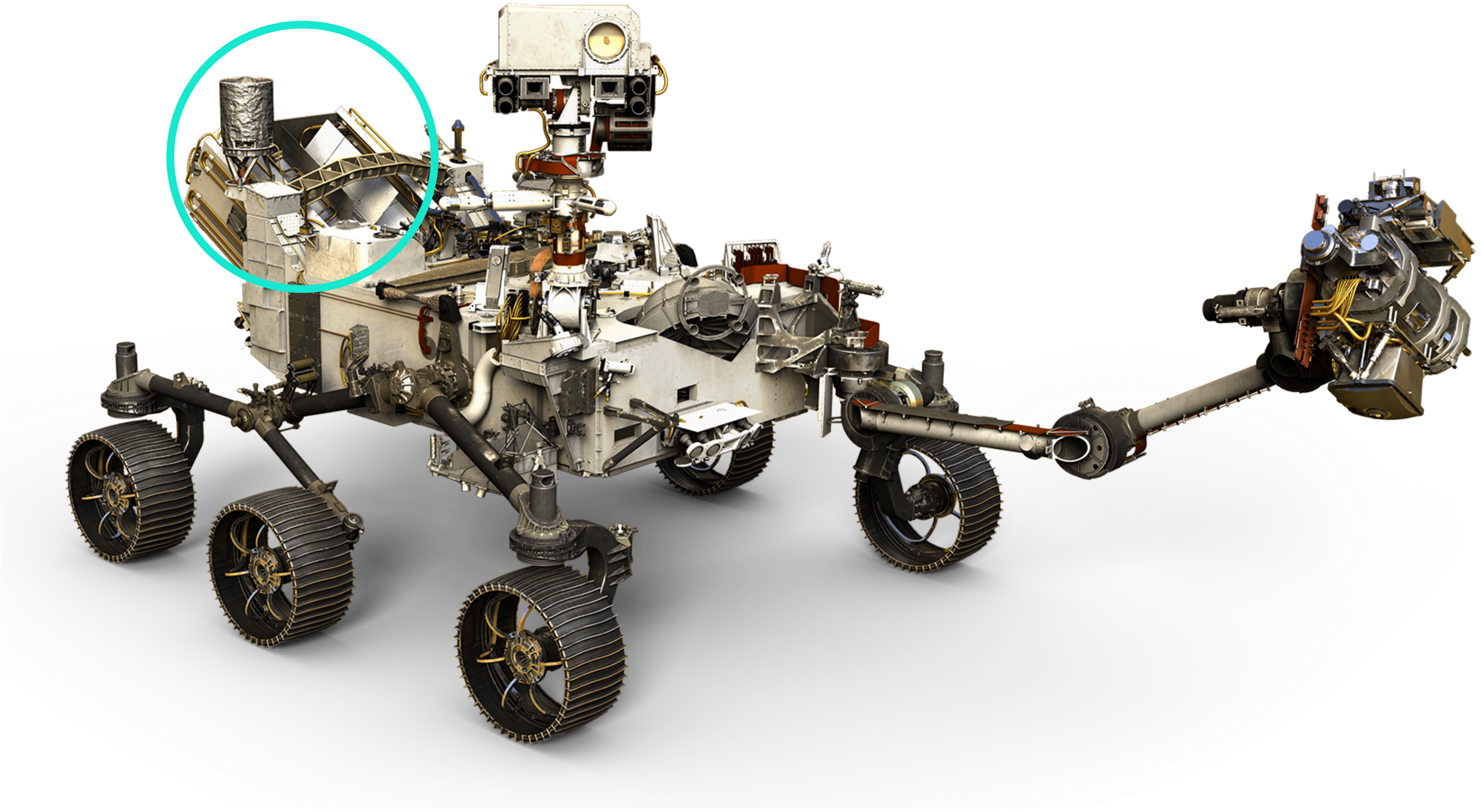
Structure

- Called the Warm Electronics Box (WEB)
- Closed on top by Rover Equipment Deck, on which is mounted the camera masts
- 10 ft. long, 9 ft. wide, 7 ft. tall (3x2.7x2.2 m)
- 2,260 lbs (1,025 kg)
- Able to sample and cache minerals using a coring drill



Power

- Powered by RTG, energy stored in Li-ion rechargeable batteries
- 45 kg in mass
- Uses 4.8 kg of plutonium dioxide as heat source
- 110W at launch
- Enables operation during day and night, and through the winter season



Communications

UHF antenna

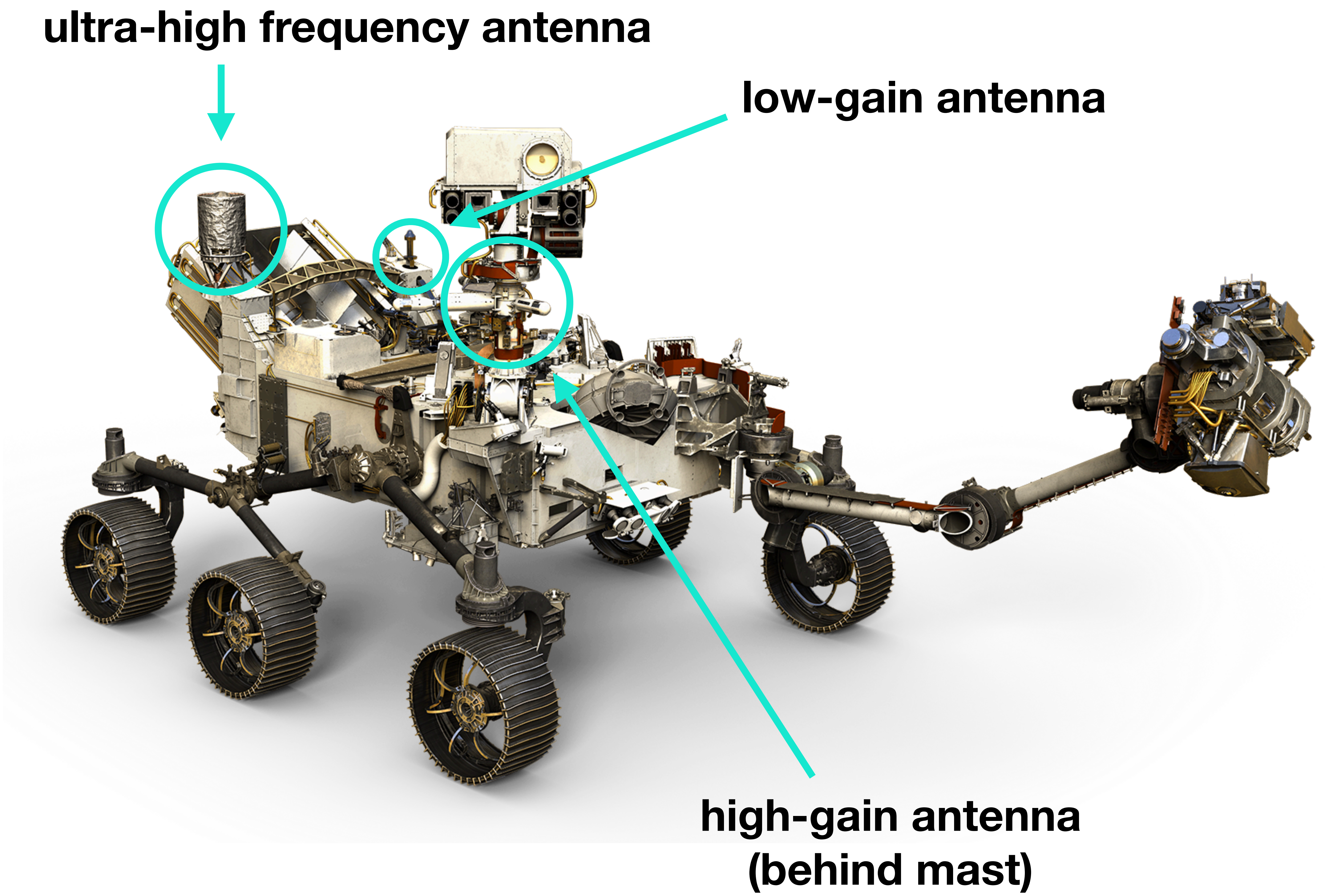
- Communicates with orbiters around Mars at 400 MHz
- Capable of 2 Mbps to the overhead orbiters

High-gain X-band

- Steerable, transmits directly to Earth in X band (7-8 GHz)
- Hexagonal, 0.3m in diameter
- $\geq$160/500 bps to/from the Deep Space Network 34m antennas
- $\geq$800/3000 bps to/from DSN's 70m antennas

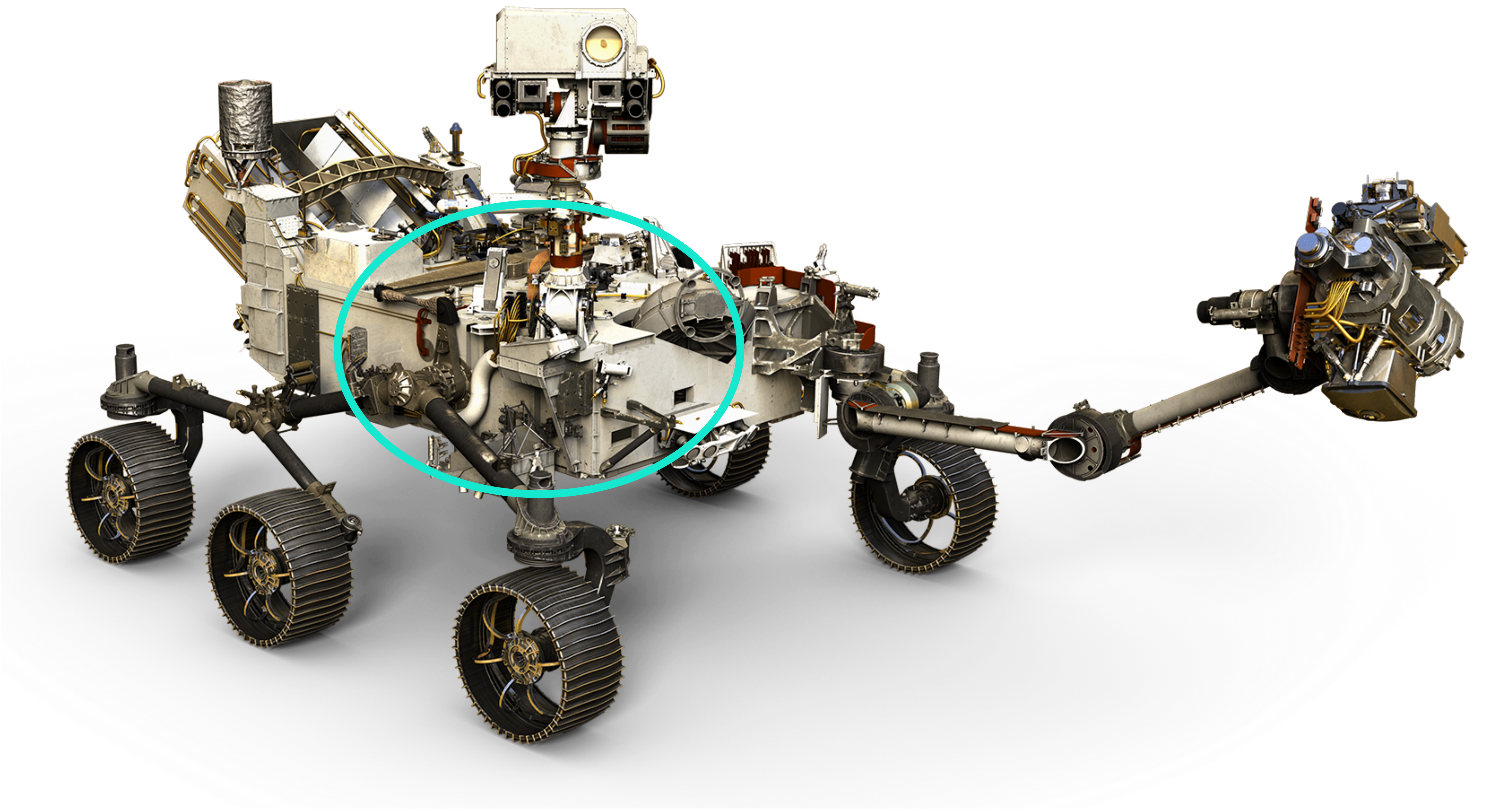
Low-gain X-band

- Omnidirectional, mostly used for receiving
- $\geq$10 bps to 34m DSN, $\geq$30 bps to DSN 70m

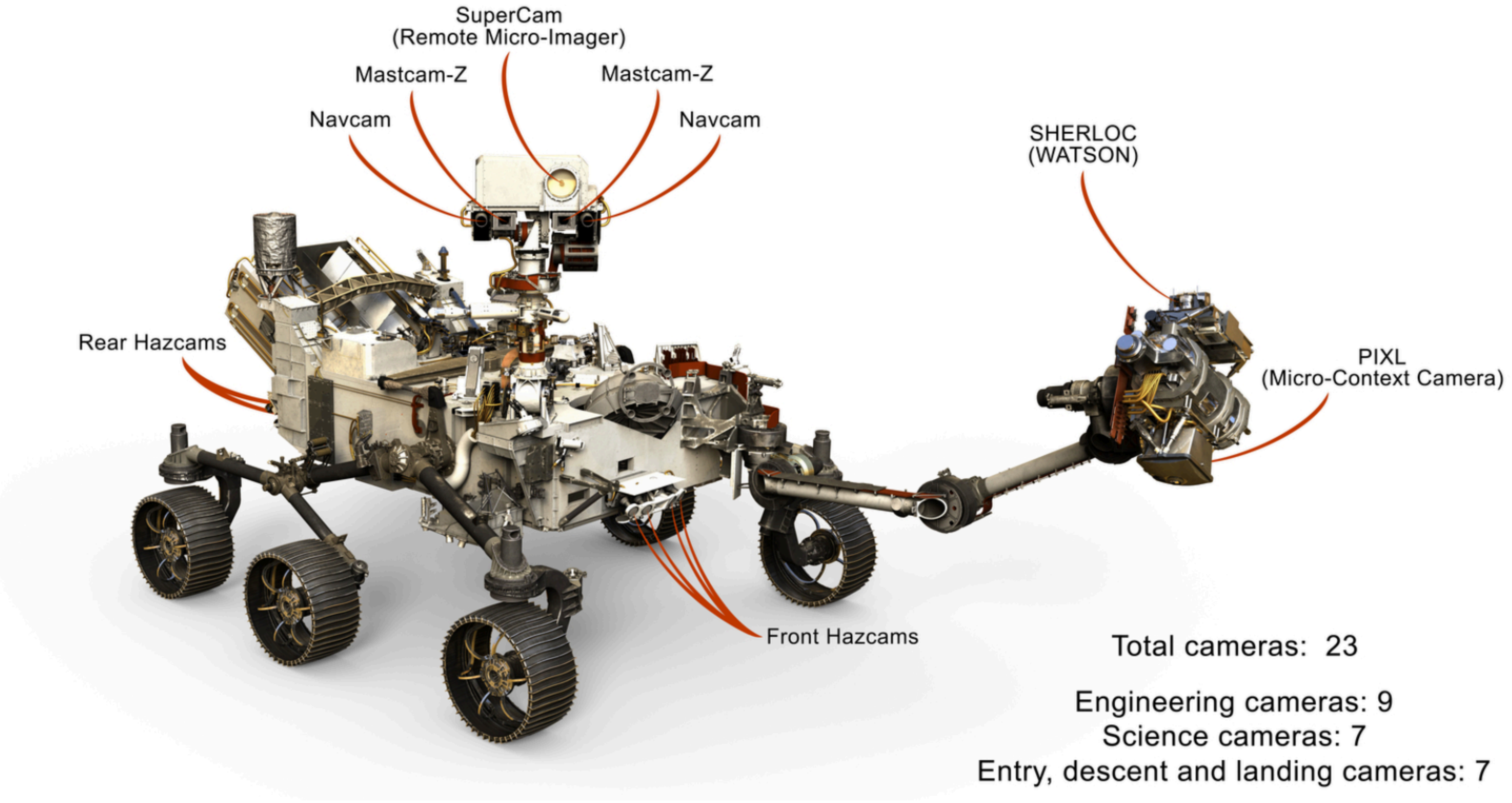


Computation

- Two redundant Rover Compute Elements (RCE’s)
- Radiation-hardened central processor operating at 200 MHz (PowerPC 750 Architecture)
- 2 GB flash memory
- 256 MB of RAM
- 254 kB of electrically erasable programmable read-only memory
- Carries an IMU
- Temperature/power generation monitoring



Cameras

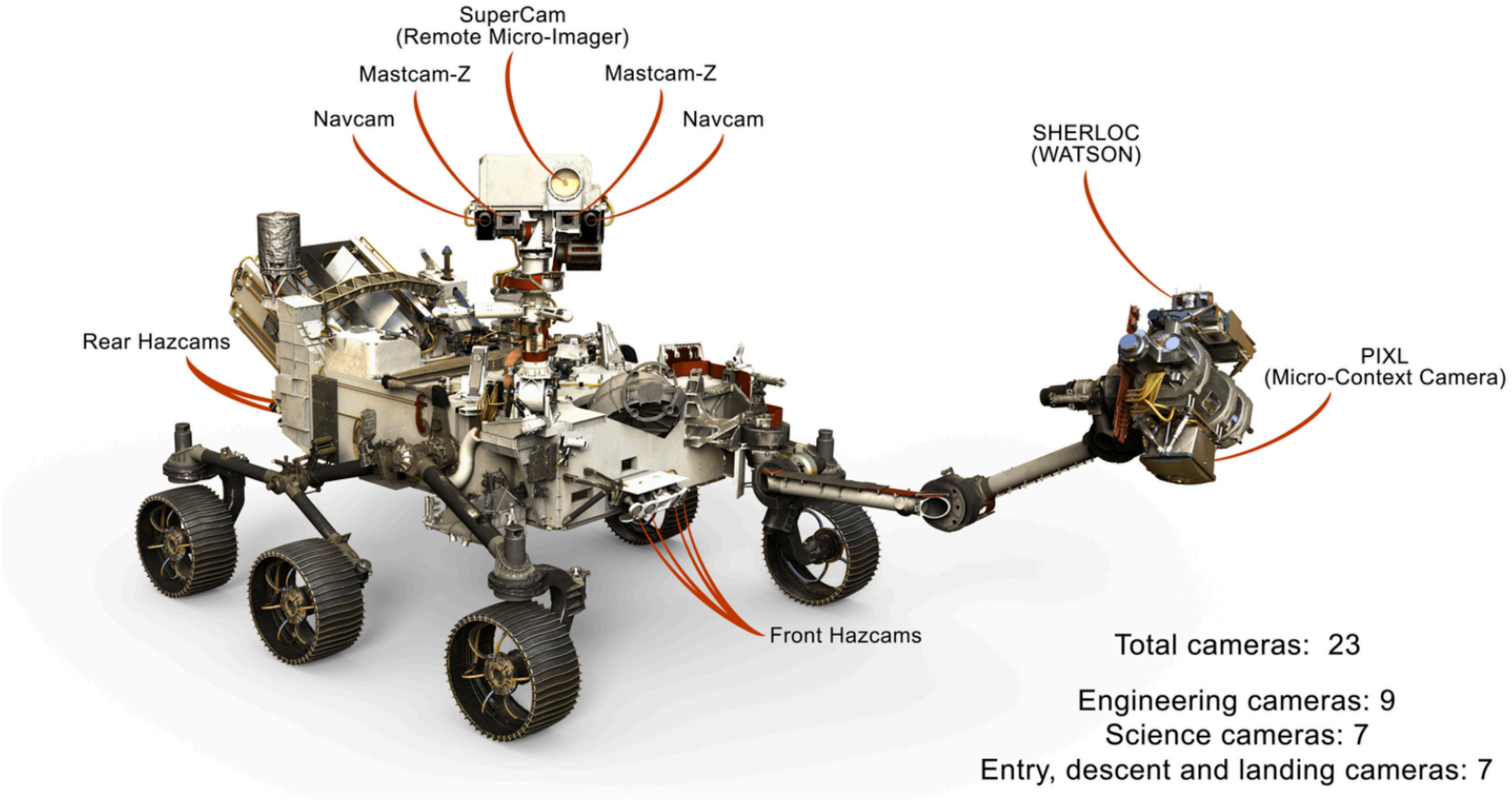


Total cameras: 23

Engineering cameras: 9
Science cameras: 7
Entry, descent and landing cameras: 7

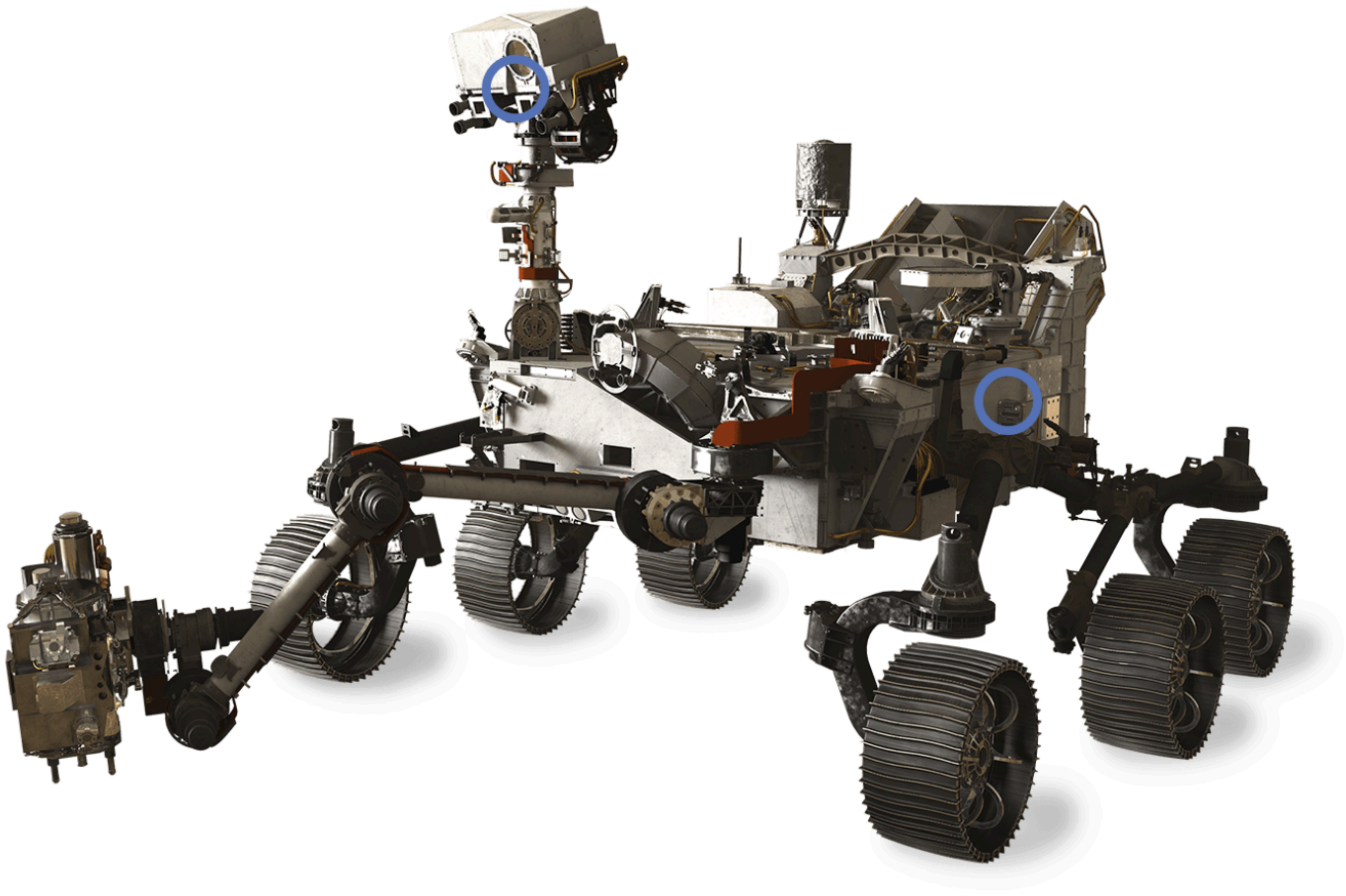
Cameras

- Several cameras and microphones to document EDL **in full-color video** (looking up at parachutes, looking down at the rover, looking up from the rover at the descent stage, looking down at the ground)
- Engineering cameras for driving, hazard avoidance, and navigation
- CacheCam for looking down the top of the sample cache, records the entire process by which samples are collected
- A suite of science cameras for zoom images, laser spectroscopy, chemical analysis



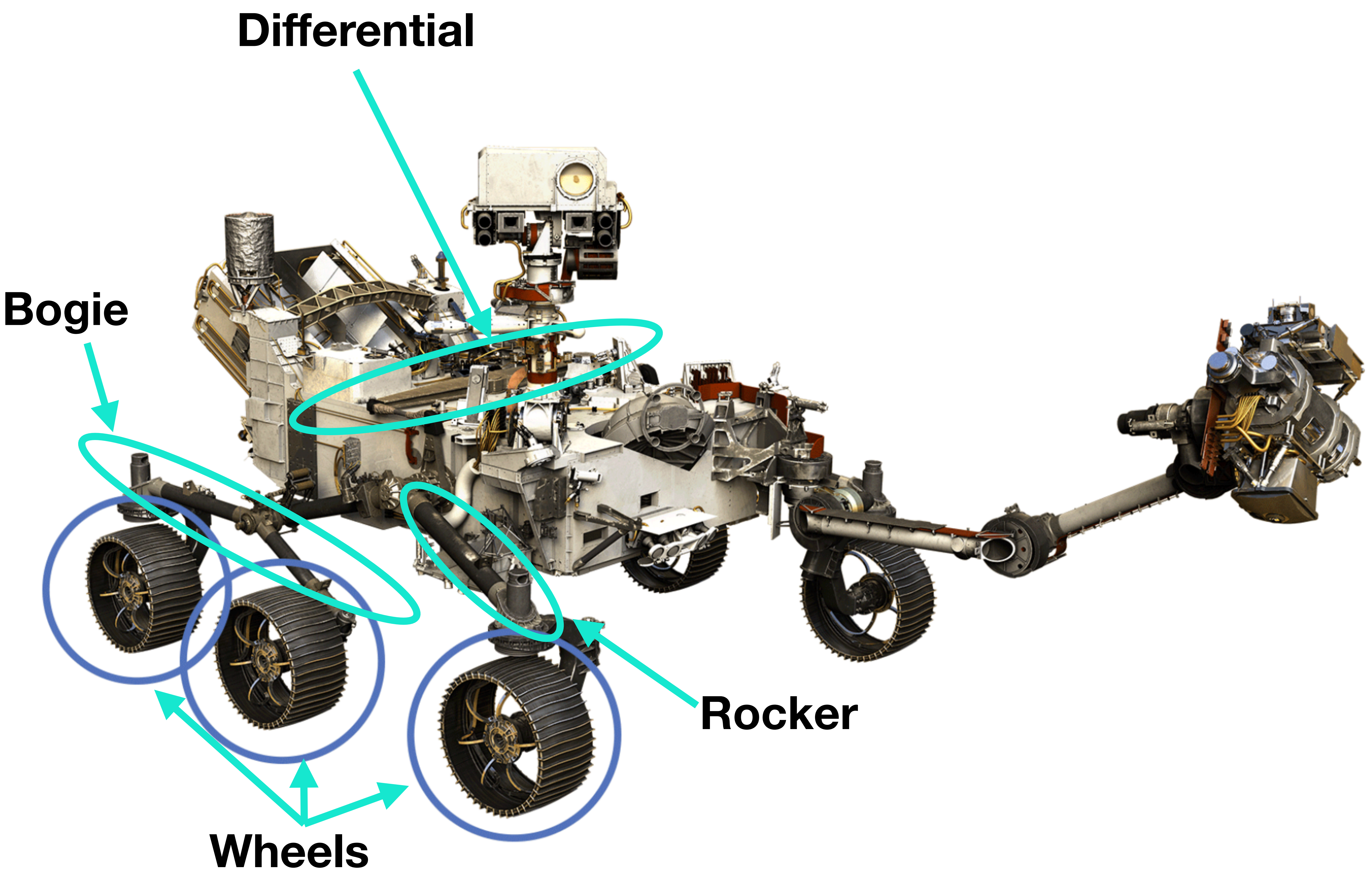
Microphones

- Listens to the sound of rock being vaporized by laser, which informs scientists of the mass and makeup of that rock
- Listens also to the wind, the sound of the dust blowing across the rover, passing dust devils
- Another microphone records the sounds throughout EDL (friction with the atmosphere, wind, the sounds of dust displaced as the rover approaches the ground)
- If this microphone survives landing (unlikely) it will record the sounds of wheels turning, motors turning the rover's head, and heat pumps that keep it warm.



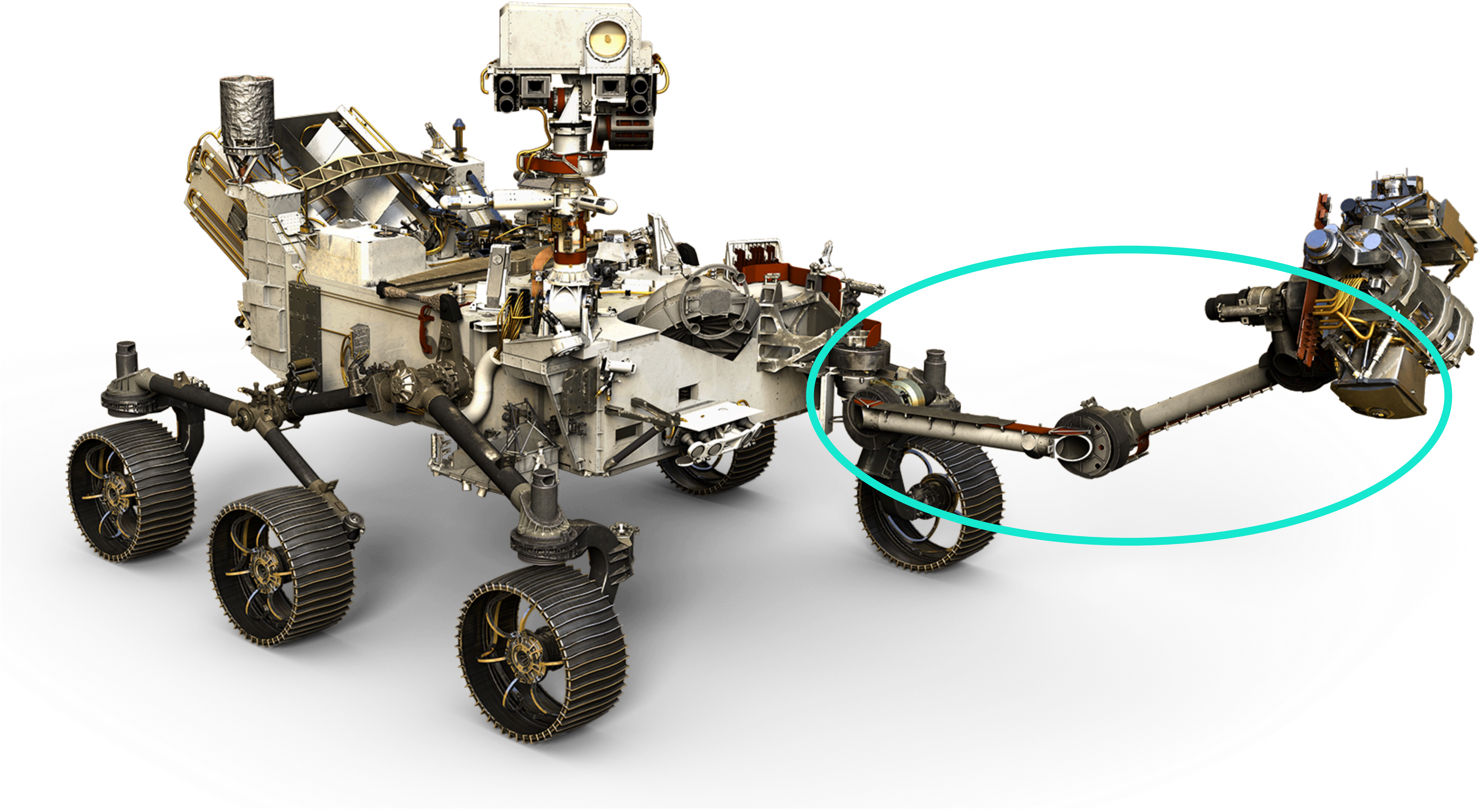
Wheels and suspension

- 6 wheels, each with its own motor
- The two front and rear wheels have individual steering motors
- Legs are made of titanium tubing (manufactured using the same process as mountain bike frames)
- Wheels are aluminum, with cleats for traction and curved titanium spokes
- Employs a “rocker-bogie” suspension system
  - Differential connects left and right rockers and to the rover body by a pivot on the rover’s top deck
  - Rocker connects the front wheel on each side to the differential and the bogie in the rear
  - Bogie connects the middle and rear wheels to the rocker
  - Designed to maintain relatively even loading over uneven terrain, and to minimize tilt
  - Capable of standing at 45 deg without tipping (to be safe, the operators won’t exceed 30 deg)
- Top speed of 4.2 cm/s



Arm

- 7 feet long
- 5 degrees of freedom
- Hand turret that carries scientific cameras, mineral/chemical analyzers, and cache collection
- Carries a drill with interchangeable bits



Sample management

- Uses drill to gather and store samples of Martian rock and soil
- Samples will be stored in tubes, and then deposited on the Martian surface (at a well-identified place)
- In addition to sample collection tubes, the rover carries “witness tubes” that will be exposed to the ambient environment as samples are collected so that any contamination of the sample can be measured
- Tubes are hermetically sealed and stored in the belly on the rover until the team decides on a good place to leave them
- In the future, they will be recovered and returned to Earth