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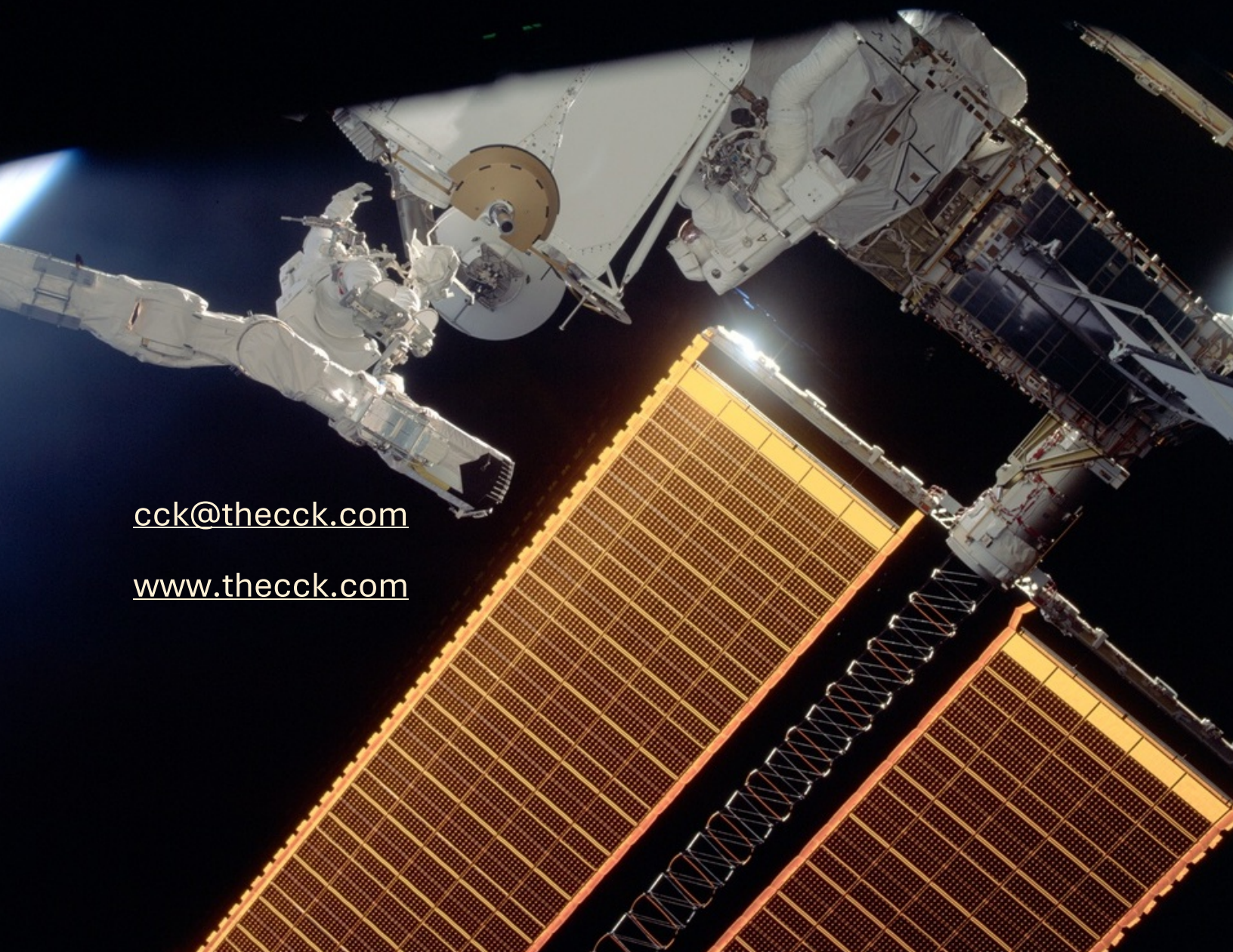
CANADARM2

From Earth to Orbit

A prototype developed for educational review and discussion

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Canadarm2 From Earth to Orbit

Preface

This problem-based article follows the real journey of Canadarm2 from the launch pad in Florida to its first movements on the International Space Station. The narrative is based on records from NASA and the Canadian Space Agency. No invented dialogue or emotions have been attributed to real people. Whenever a physical model simplifies the actual mission, the assumption is stated explicitly. Unless otherwise noted, times are given in Eastern Daylight Time (EDT).

1) Waiting for a Seventeen-Metre Arm to Fly

On the morning of Thursday, April 19, 2001, Space Shuttle *Endeavour* stood on Launch Pad 39A at Kennedy Space Center in Florida. Mission commander Kent Rominger, pilot Jeffrey Ashby, and five mission specialists were about to begin one of the most complex sets of robotic operations yet attempted in the Shuttle program: transporting Canadarm2 to the International Space Station and assisting with its installation. Among the crew was Canadian Space Agency astronaut Chris Hadfield [1, 2].

Inside the payload bay of the Space Shuttle *Endeavour*, a 17.6-metre structure was secured to a special pallet: Canadarm2, a 1,497-kilogram robotic arm with seven degrees of freedom and two identical "hands." Either end could grasp an object or attach to the Station [3]. Before Canadarm2, Canada had developed a robotic arm officially named *Canadarm*. Several units were built for the Space Shuttle fleet. The first flew on mission STS-2 in 1981. Mounted beside a Shuttle's payload bay, Canadarm kept one end attached to the orbiter and used the other to grasp and move payloads. *Endeavour* carried one of these first-generation arms on STS-100 [4].

Canadarm2 was the next generation, designed to work permanently on the International Space Station. The Shuttle Canadarm was 15.2 metres long and could not relocate its base. Canadarm2 was approximately 2.4 metres longer, and either end could attach to dedicated points on the Station. By releasing one end only after securing the other, the arm could "walk" across the Station. The number 2 distinguishes this system from the original Shuttle Canadarms [3, 4].

At 2:40:35 p.m. on April 19, 2001, the main engines of *Endeavour* ignited. Approximately 6.6 seconds later, at 2:40:42 p.m., the Shuttle lifted off from Kennedy Space Center. About eight and a half minutes after launch, the main engines shut down. The Shuttle was not yet in a stable orbit; without a further maneuver, its path would have brought it back

into Earth's atmosphere. After the external tank separated, the orbital maneuvering engines increased the Shuttle's speed. This raised the perigee, the point in the orbit closest to Earth, and placed *Endeavour* in a stable orbit below the International Space Station. Over the next 43 hours, a sequence of carefully planned maneuvers adjusted the Shuttle's altitude and timing. During the final approach, its direction and velocity were matched to those of the Station until their relative velocity was nearly zero. *Endeavour* docked with the International Space Station at 9:59 a.m. on April 21 [1]. The data in Tables 1, 2, and 3 at the end of the article are needed to answer the following questions.



Figure 1) Space Shuttle *Endeavour* launches on mission STS-100, April 19, 2001. Credit and source: [NASA](#). NASA image, public domain in the United States.

Question 1

The actual orbits of *Endeavour* and the International Space Station were not perfectly circular, and their altitude changed during each revolution. Near the time of docking, the orbital altitude was approximately 331 to 375 kilometres. To simplify the calculations, model the orbit as a circle at the rounded mean altitude $h = 350$ km.

a) Calculate the speed required for a circular orbit at altitude h , express it in kilometres per hour, and compare it with the approximate value of 28,000 kilometres per hour reported by the Canadian Space Agency for the Station's motion [5].

Hint: In a circular orbit, gravity supplies the centripetal force. The distance from Earth's centre is $r = R_E + h$.

b) What is the kinetic energy of Canadarm2 at the orbital speed found in part a?

c) By how much does its gravitational potential energy increase between Earth's surface and an altitude of 350 kilometres?

d) In this simplified model, what fraction of the calculated increase in mechanical energy is associated with the increase in gravitational potential energy, and what fraction is associated with orbital kinetic energy? Ignore atmospheric resistance, Earth's rotation, and propulsion losses.

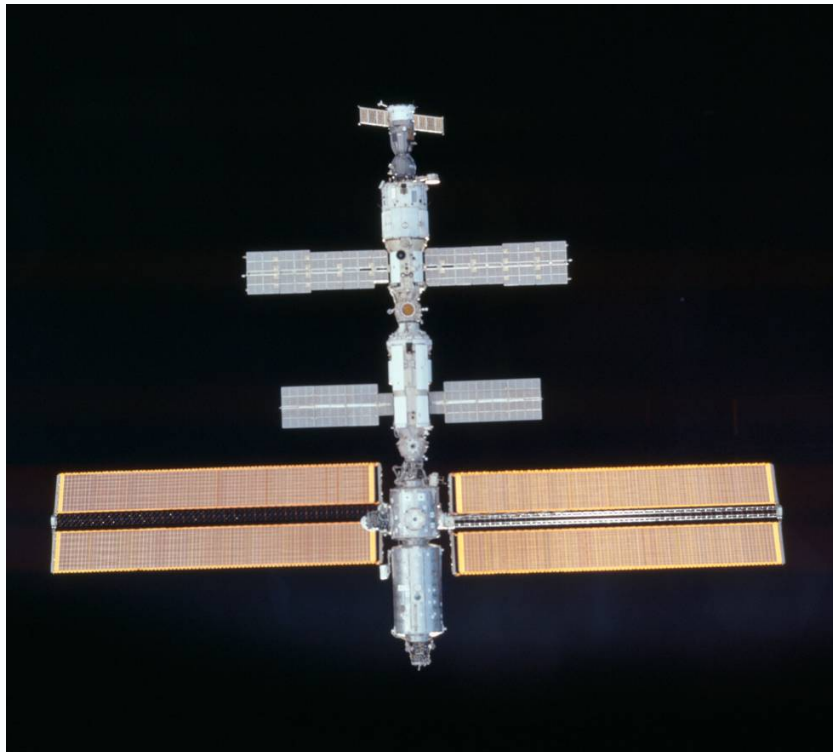


Figure 2) The International Space Station, viewed from *Endeavour* during the approach and docking phase of STS-100. Credit: NASA. Public domain. [Image source and mission account](#).

Solution 1

a) Equating the gravitational and centripetal forces gives

$$v = \sqrt{\frac{GM_E}{r}} = \sqrt{\frac{3.986 \times 10^{14}}{6.721 \times 10^6}} \approx 7.7 \times 10^3 \text{ m/s} = 7.7 \text{ km/s} \approx 27\,720 \text{ km/h.}$$

Where $r = R_E + h = 6.371 \times 10^6 + 3.50 \times 10^5 = 6.721 \times 10^6 \text{ m}$.

The calculated result is close to the Canadian Space Agency's stated approximate value of 28 000 km/h. Both values are approximate. The calculated value of 27,720 km/h is based on an idealized circular orbit at a fixed altitude. In practice, orbital speed varies slightly as the altitude changes, while the Canadian Space Agency's value of 28,000 km/h is a rounded representative value.

b) The orbital kinetic energy of Canadarm2 is approximately $K = \frac{1}{2}mv^2 \approx 44.39 \text{ GJ}$.

c) The increase in gravitational potential energy is $\Delta U = GM_E m \left(\frac{1}{R_E} - \frac{1}{R_E + h} \right) \approx 4.88 \text{ GJ}$.

d) The calculated increase in mechanical energy is $\Delta E = 44.39 + 4.88 = 49.27 \text{ GJ}$.

The kinetic-energy share is $\frac{44.39}{49.27} \times 100 \approx 90\%$, so the gravitational-potential-energy share is approximately 10%.

In this idealized calculation, the energy associated with reaching orbital speed is much greater than the energy associated with gaining altitude. About 90 percent of the calculated increase in mechanical energy is orbital kinetic energy, while only about 10 percent is the increase in gravitational potential energy. Reaching orbit is therefore not simply a matter of climbing high enough: a spacecraft must also acquire a very large tangential speed.

This result is only the increase in the mechanical energy of Canadarm2, not the actual energy consumed to deliver it to orbit. The Shuttle, tanks, crew, and other payloads also had to be accelerated and lifted, while energy was transferred to exhaust gases and the surrounding environment.

2) A Meeting After Forty Three Hours

Although *Endeavour* entered a stable orbit soon after launch, reaching the International Space Station took about 43 hours. Entering Earth orbit did not mean that the Shuttle was already in the same orbit and at the same location as the Station. Its path and timing had to be adjusted so that the two spacecraft arrived at the same point, with almost no difference between their velocities.

At 9:59 a.m. on April 21, Rominger gently docked *Endeavour* to the forward port of *Destiny*, the United States research laboratory on the International Space Station. Exactly 43 hours, 18 minutes, and 18 seconds had passed since launch [1].

Question 2

- a) Using the orbital speed calculated in Question 1, determine the period of a circular orbit at an altitude of 350 kilometres.
- b) Approximately how many times did the International Space Station orbit Earth between the Shuttle's launch and docking?

Solution 2

The circumference of the model orbit is $2\pi r$, so

$$T = \frac{2\pi r}{v} = \frac{2\pi(6.721 \times 10^6)}{7.7 \times 10^3} \approx 5.485 \times 10^3 \text{ s} \approx 91.4 \text{ min.}$$

The elapsed time from launch to docking was 2 598.3 min. Therefore, $N = \frac{2\,598.3}{91.4} \approx 28.43$. Within this approximate model, the Station completed about 28 full orbits and part of its twenty-ninth orbit during that interval.

3) Installation Begins Behind Closed Hatches

Endeavour had docked, but the hatches remained closed. Chris Hadfield and NASA astronaut Scott Parazynski were scheduled to leave the Shuttle less than a day later and begin installing Canadarm2. To reduce the risk that dissolved nitrogen would form bubbles in their bodies when they entered their low-pressure spacesuits, the Shuttle cabin pressure had been reduced before docking from about 14.7 to 10.2 psi. The two astronauts were not yet wearing their spacesuits.

The Station remained at a higher pressure. Opening the hatches would have raised the Shuttle's pressure again and disrupted the astronauts' preparation. The two crews therefore postponed their face-to-face meeting until April 23. In the meantime, they exchanged only a few items through the closed vestibule between the spacecraft [2].

On April 22, the first generation of Canadarm came to the aid of its successor. From inside *Endeavour*, Jeffrey Ashby operated the robotic arm attached to the Shuttle. He lifted the pallet carrying Canadarm2 and a UHF antenna out of the payload bay and temporarily attached it to the exterior of *Destiny*. Chris Hadfield and Scott Parazynski then left the Shuttle's airlock [2].

This was the first spacewalk by a Canadian. Their task involved far more than opening a package: they had to install the antenna, release eight bolts that secured the arm, unfold its two long sections by hand, and connect communication cables to the Station. Inside *Destiny*, Susan Helms and James Voss used the robotics workstation to verify Canadarm2's power and data connections. The first spacewalk lasted 7 hours and 10 minutes [1, 2].



Figure 3) Scott Parazynski unfolds Canadarm2 during the mission's first spacewalk on April 22, 2001. Credit: NASA, image STS100-395-022. Public domain. [Source page](#).

Question 3

Model the 1,497-kilogram Canadarm2 at an orbital altitude of 350 kilometres.

- a) Calculate the gravitational force acting on it at this altitude.
- b) What percentage is this force of the gravitational force acting on the same arm at Earth's surface?
- c) Given your answers to parts a and b, why did Hadfield, Parazynski, and their tools appear weightless, and why could they maneuver such a massive arm?
- d) Hadfield and Parazynski's first spacewalk lasted 7 hours and 10 minutes. If the Station completed one orbit in approximately 91.4 minutes and experienced one orbital day-night cycle per orbit, approximately how many cycles occurred during the spacewalk?

Solution 3

a)
$$F_g = \frac{GM_E m}{r^2} \approx 1.32 \times 10^4 \text{ N.}$$

b) At Earth's surface, the corresponding force is approximately $1.47 \times 10^4 \text{ N}$. Therefore,

$$\frac{1.32 \times 10^4}{1.47 \times 10^4} \times 100 \approx 89.8\%.$$

Gravity at the Station's modelled altitude is still about 90 percent as strong as it is at Earth's surface.

c) Weightlessness does not result from the absence of gravity. Canadarm2, the astronauts, and the Station were all accelerating together in free fall. The support force that we normally experience as weight was therefore absent. The arm still had substantial inertia, so moving and stopping it required careful control even though the astronauts did not have to support its Earth weight.

d) The Station normally enters and leaves Earth's shadow once per orbit, completing one day-night cycle. The spacewalk lasted 430 minutes, so $\frac{430}{91.4} \approx 4.7$.

The astronauts therefore experienced approximately five orbital day-night cycles. Depending on the exact illumination at the beginning and end of the spacewalk, they could have observed four or five sunrises.

Did you know? During this spacewalk, residue from antifogging solution inside Chris Hadfield's helmet irritated one eye. In microgravity, tears do not run down the face; they collect around the eye. Hadfield's tears reached his other eye and temporarily impaired his vision. Following instructions from Mission Control, he increased the oxygen flow through his helmet. The liquid gradually evaporated, and he continued working [6].

For at least a few minutes that day, installing the 1,497-kilogram Canadarm2 seems to have caused Hadfield less trouble than moving a thin layer of tears.



Figure 4) Chris Hadfield during the first EVA of STS-100. Credit: NASA, image STS100-395-032. Public domain. [High-resolution file and licence information.](#)



Figure 5) Susan Helms and James Voss control Canadarm2's first movements from inside *Destiny*. Credit: NASA. Public domain. [Image source and mission account](#).

Question 4

Note: This question is a thought experiment, not an event that occurred during the mission. Suppose Canadarm2 became completely detached from the Station while in the modelled 350-kilometre orbit, without being pushed and without receiving any additional relative velocity. Ignore the thin atmosphere and the gravitational effects of other bodies.

- Would the arm fall directly to Earth's surface?
- Would an engine need to remain continuously on to keep it in orbit?
- Why would an uncontrolled separation still be extremely dangerous in practice?

Solution 4

- At the instant of separation, the arm would have the same velocity and direction as the Station. In the idealized model, it would therefore enter a nearly identical orbit rather than falling directly to Earth.
- An engine would not need to remain continuously on. Gravity supplies the centripetal force that continually bends the arm's path around Earth.
- A very small relative velocity would place the arm in a slightly different orbit. It could drift away from the Station or return toward the structure and create a collision hazard. Canadarm2 is attached not to hold it up against gravity, but to control its position, transfer power and data, and prevent uncontrolled relative motion.

4) The Arm Takes Its First Steps

On April 23, the hatches finally opened and the two crews met face to face. Outside, another important moment arrived for the Canadian robot. Helms and Voss activated Canadarm2 from the workstation inside *Destiny*. One end released the transport pallet while the other attached to a Power Data Grapple Fixture on the laboratory, which supplied power, data, and video connections. The arm had taken its first "step" [2, 3].

Canadarm2 has no wheels. Either end can act as a hand or as an anchoring foot. One end is not released until the other is securely latched and its power and data connections are established. In this way, Canadarm2 can move end over end, or "hand over hand," among attachment points on the Station [3].

5) An Electrical Fault a Computer Failure and a Canadian Handshake

On April 24, Hadfield and Parazynski went outside for a second time. They completed the power and data circuits at the arm's attachment point. The work did not proceed without difficulty: the backup power circuit initially failed to respond to commands. Disconnecting and reconnecting cables at the arm's base corrected the problem [1].

Soon afterward, one of the Station's three command-and-control computers failed, interrupting direct communication between Mission Control in Houston and the Station's United States systems. Communication was temporarily routed through *Endeavour*, and robotic operations were delayed. Investigation showed that the hard drive in computer number one had failed; a backup computer took over [1].

Canadarm2 and the UHF antenna had travelled to orbit on a special transport pallet. After they were installed on the Station, the empty pallet remained outside, temporarily held by Canadarm2. On the tenth day of the mission, Chris Hadfield operated the first-generation Canadarm from inside the Shuttle and grasped the empty pallet. After the connection was confirmed, Susan Helms commanded Canadarm2 from inside *Destiny* to release it. Canadarm2 had handed the pallet to the Shuttle Canadarm, and Hadfield returned it to *Endeavour's* payload bay for the trip back to Earth. This direct transfer between two Canadian robotic arms became known as the "Canadian handshake" [1, 2].

On April 29, *Endeavour* undocked from the Station. During the Shuttle's fly-around, Canadarm2 appeared for the first time in farewell photographs as part of the orbiting structure. The Shuttle landed at Edwards Air Force Base in California on May 1. Canadarm2 remained in space, attached to and supporting the International Space Station [2, 3].



Figure 6) Transfer of the transport pallet from Canadarm2 to the Shuttle Canadarm, known as the Canadian handshake. Credit: NASA, image STS100-347-007. Public domain.

[High-resolution file and licence information.](#)

Table 1) Equations Used

Concept	Equation	Use in the investigation
Distance from Earth's centre	$r = R_E + h$	Convert orbital altitude to orbital radius
Newtonian gravitation	$F_g = GM_E m/r^2$	Calculate the gravitational force on the arm
Centripetal force	$F_c = mv^2/r$	Model a circular orbit
Circular orbital speed	$v = \sqrt{GM_E/r}$	Find the required speed at 350 km altitude
Orbital period	$T = 2\pi r/v$	Calculate the duration of one orbit
Kinetic energy	$K = mv^2/2$	Calculate the arm's energy of motion in orbit
Change in gravitational potential energy	$\Delta U = GM_E m(1/R_E - 1/r)$	Calculate the energy change associated with increasing altitude
Approximate number of orbits	$N = \Delta t/T$	Compare an event's duration with the orbital period
Estimated orbital distance	$d = N(2\pi r)$	Estimate cumulative travel over an extended interval



Figure 7) Canadian Space Agency astronaut Chris Hadfield wearing a training version of the Extravehicular Mobility Unit (EMU) spacesuit. Photograph by Robert Markowitz, NASA Johnson Space Center, July 19, 2011. NASA Photo ID: JSC2011-E-203354. Cropped from the original. Public domain. [Image source](#).

Table 2) Data for Question 1

Quantity	Symbol	Value
Mean radius of Earth	R_E	$6.371 \times 10^6 \text{ m}$
Earth's standard gravitational parameter	GM_E	$3.986 \times 10^{14} \text{ m}^3/\text{s}^2$
Modelled orbital altitude	h	$3.50 \times 10^5 \text{ m}$
Mass of Canadarm2	m	1 497 kg

Table 3) Data and Model Assumptions

Item	Value or assumption
Mean radius of Earth	6.371×10^6 m
Earth's standard gravitational parameter	3.986×10^{14} m ³ /s ²
Modelled Station altitude	350 km
Mass of Canadarm2	1 497 kg
Length of Canadarm2	17.6 m
Duration of first EVA	7 h 10 min
Duration of second EVA	7 h 40 min
Educational model	Spherical Earth; circular orbit; negligible atmospheric resistance; gravitational effects of other bodies ignored.

Table 4) Twenty-Five Years Later: A Short History of an Arm That Never Sleeps

Year	Documented event
1981	The original Canadarm made its first flight on STS-2, beginning Canada's legacy in space robotics [4].
2001	Canadarm2 was launched on STS-100 and connected to the Station during two spacewalks. Hadfield became the first Canadian to perform a spacewalk [1, 7].
2002	One of the arm's wrist roll joints was replaced in orbit, an early demonstration of its modular and repairable design [3].
2006	The Royal Canadian Mint issued a coin featuring Hadfield and Canadarm2 [3].
2008	The two-armed robot Dextre arrived at the Station and joined Canada's robotic system. Canadarm2 moves Dextre around the Station [8].
2009 onward	In addition to assembly and maintenance, the arm began capturing and berthing uncrewed cargo spacecraft in operations known as "cosmic catches" [5].
2011	The Space Shuttle program ended and the original Canadarm retired after 30 years. Canadarm2 continued working in orbit [4].
2013	Canadarm2 and Dextre appeared on Canada's polymer five-dollar banknote [3].
2017 and 2018	Astronauts replaced the arm's two Latching End Effectors, its robotic "hands" [3].
2026	Twenty-five years after its installation, Canadarm2 continues to help maintain the Station, move equipment, and capture some cargo spacecraft [3, 5].

Table 5) Alignment with the British Columbia Curriculum

BC course and learning standard	Connection to this investigation	Relevant sections
Physics 12 content: uniform circular motion, including centripetal force and acceleration	Students equate gravitational force with centripetal force and calculate circular orbital speed and period.	Questions 1 and 2
Physics 12 content: gravitational field and Newton's law of universal gravitation	Students calculate gravitational force in orbit and compare it with surface gravity.	Question 3
Physics 12 content: gravitational potential energy and gravitational dynamics and energy relationships, including satellite motion, orbit changes, and launch velocity	Students compare kinetic and potential energy changes, interpret orbital insertion, and explain why sustained thrust is not required in an ideal orbit.	Questions 1 and 4
Physics 12 content: frames of reference and relative motion	The rendezvous narrative distinguishes high orbital speed from the small relative velocity required for docking.	Section 2 and Question 4
Physics 11 content: mass, force of gravity, apparent weight, Newton's laws, and conservation of energy	Students distinguish gravitational force from apparent weight and apply energy relationships in a real context.	Questions 1 and 3
Physics 11 and 12 curricular competency: use SI units, significant figures, uncertainty, and scientific notation	All numerical work uses SI quantities, powers of ten, conversions, and approximate measured or reported data.	Questions 1 to 3 and Tables 1 to 3
Physics 11 and 12 curricular competency: analyze data, identify relationships, perform calculations, and draw evidence-based conclusions	Students compare a calculated orbital speed with a published value and interpret ratios and model outputs.	Questions 1 to 3
Physics 11 and 12 curricular competency: construct and evaluate models and recognize assumptions and limitations	The article explicitly models Earth as spherical and the orbit as circular, then distinguishes model results from the real mission.	All questions, especially Questions 1 and 4
Physics 11 and 12 curricular competency: communicate scientific ideas using appropriate language, conventions, and representations	Students connect equations, units, historical evidence, and written explanations for a general audience.	Entire investigation

References

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