Project Hail Mary Challenge Competition Handbook

Students design the space station. Teachers fly it in microgravity.

SPACE
FOR TEACHERS

Project Hail Mary Challenge
Competition Handbook

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Version 1.0 — January 2026

At a Glance

Submission Deadline	May 4, 2026
Divisions	Division I (K–8) | Division II (High School)
Prizes	Two winning educators fly their students' designs on a parabolic aircraft (Fall 2026)
Submission Portal	spaceforteachers.org/projecthailmary
Questions	laura@spaceforteachers.org

About This Program

The Project Hail Mary Challenge is a program of *Space for Teachers*, developed in collaboration with the Wisconsin Space Grant Consortium, Carthage College, and the University of Texas Center for Space Research.

How to Use This Handbook

Sections 1–8 contain everything needed to enter the competition: challenge overview, eligibility requirements, design constraints, submission requirements, and evaluation criteria.

Appendices A and B provide detailed measurement and testing procedures. Review these appendices before beginning spin testing with your students.

Teachers are encouraged to read the full handbook before starting the project, then return to specific sections as reference during implementation.

Copyright and Usage

1 Introduction

Teachers are at the center of this story.

Students design the space station. Teachers fly it in microgravity.

The **Project Hail Mary Challenge** is a national classroom competition inspired by Andy Weir's novel *Project Hail Mary* and timed to coincide with the upcoming film adaptation. Students step into the role of spacecraft designers, creating small-scale rotating space stations that turn the film's artificial gravity concept into real engineering work.

Two winning educators (one K-8, one High School) will partner with Space for Teachers to build and fly their students' design on a parabolic aircraft to see how it performs in microgravity. Entries are evaluated on technical feasibility, scientific accuracy, testing and safety planning, student engagement, community outreach, aesthetic design, and presentation quality.

Key Dates

Milestone	**Date**
Submissions Open	February 5, 2026
Submission Deadline	May 4, 2026
Winner Announced	June 1, 2026
Parabolic Flight	Fall 2026 (date TBD)

All submissions must be uploaded to the competition portal by 11:59 PM (your local time) on May 4, 2026. Late submissions cannot be considered.

Winners will be notified via email and announced publicly on the Space for Teachers website. Winning educators will coordinate with Space for Teachers to prepare their students' design for the parabolic flight, with flight logistics and travel details provided upon selection.

Questions? Contact laura@spaceforteachers.org or visit the project FAQ at https://spaceforteachers.org/projecthailmary

1.1 The Challenge

Your class will act as a **Spacecraft Design and Ground Verification Team**. Your mission is to:

1. **Design** a safe, small-scale model of a rotating "artificial gravity" space station.
2. **Build** a physical model consisting of two modules (a Crew Compartment and a Propulsion Module) connected by a tether.
3. **Prove** that the design works by spinning it here on Earth to generate artificial gravity.

All completed models will be featured in an online gallery of team submissions that will serve as a companion site for educators to explore the science of Project Hail Mary.

1.2 The Concept: Artificial Gravity

The station uses rotation to create the sensation of gravity. This concept was first popularized by the rocket scientist Wernher Von Braun in 1952, who introduced the concept of a rotating "wheel" in space as a means of establishing a constant acceleration for occupants of the wheel-station. When the wheel spins about its center, occupants standing on the inside surface of the outer rim experience an outward push—their feet press against the floor as if gravity were pulling them toward the outside of the wheel.

Various alternative approaches to artificial gravity have been proposed since the "Von Braun Wheel" was introduced, including the use of two separate spacecraft modules separated by a tether and spun about their Center of Mass (COM). When two connected modules spin around their shared COM, the floor of each module pushes inward on its occupants. This push is felt as "artificial gravity". This is the concept explored in the Project Hail Mary story and the one that motivates this challenge.

Because the two modules have **unequal masses**, the Center of Mass is not in the middle of the tether. This means the two modules spin at different radii, creating **two different levels of gravity**—a unique feature of the *Project Hail Mary* ship.

2 Eligibility & Team Assignments

The Project Hail Mary Challenge is designed to be a classroom-centered experience in which teachers lead their students through the full process of designing, building, and testing a rotating space-station model. The purpose of this structure is to support broad student participation, integrate the challenge into existing curriculum standards, and ensure that the project benefits the entire learning community rather than a small group of students.

- **Eligibility:** The challenge is open to all K-12 educators. Entries will be evaluated in two divisions:
  - **Division I:** K-8 (Note: Handbook procedures are written for middle school readiness; teachers of younger students should adapt as appropriate.)
  - **Division II:** High school.
- **Team Structure:** This is a classroom-centered experience. Teachers may engage a whole class, a specific club, or other teams. However, each teacher submits **one entry** on behalf of their classroom, school, or collaborative group[1].
- **Multiple Submissions:** Multiple teachers from the same school may submit separate entries if each represents a distinct classroom group.

[1] Collaborations can be across classrooms, schools, or with informal education partners.

- **Co-Led Entries:** If multiple teachers collaborate on a single entry, one teacher should be designated as the primary contact for submission and, if selected, flight coordination.
- **Teacher Role:** Teachers lead the process and, if selected, fly the payload. Students, mentored by their teacher(s), design, build, and test the hardware.
- **Resources:** Expensive materials offer no scoring advantage. Teams are encouraged to use low-cost, accessible materials (3D printed parts, standard hardware).

Students must be the primary designers of the spacecraft, though teachers should advise and provide guidance on the specific requirements of the Challenge.

2.1 Team Composition and Roles

Students serve as the design and development team for the rotating station, with the teacher determining how best to integrate the work into their course structure, schedule, and learning outcomes. The competition does not prescribe a specific team format, recognizing the diversity of classroom models across the country.

Teachers are encouraged to distribute the work across the class in a way that promotes broad participation. For example, students may take on roles such as:

- Spacecraft design and CAD modeling
- Mission patch and visual identity development
- Construction and fabrication (including 3D printing and assembly)
- Testing apparatus development
- Measurement and verification using the methods outlined in Appendices A and B
- Documentation and reporting, including engineering drawings and design rationale

This distributed structure allows students with different interests and strengths to contribute meaningfully to the final submission.

2.2 Flexibility in Implementation

The specific classroom implementation—including team size, division of labor, grading structure, and scheduling—is entirely at the discretion of the teacher. Some teachers may prefer to structure their class into multiple sub-teams, each responsible for a portion of the design; others may use rotating roles or whole-class collaboration. Any model that supports deep engagement and meaningful student learning is acceptable.

The Challenge values broad student involvement. Designs developed by whole-class teams, grade-level cohorts, or integrated STEM programs are fully encouraged. Teachers should feel free to adapt the challenge to align with curriculum standards in physics, physical science, engineering design, mathematics, or technology education.

3 Universal Design Constraints (The Rules)

Every submitted design—regardless of grade level—must meet these physical requirements to be eligible for flight.

Parameter	Limit / Requirement	Why this matters
Max Diameter	**1.0 meter** (fully deployed)	Ensures safety on standard lab turntables and within the test area.
Max Mass	**2.5 kilograms** (total system)	Keeps forces safe during high-speed rotation.
Max Rotation	**40 RPM** (Revolutions Per Minute)	Prevents excessive kinetic energy and tether strain.
Max g-level	**0.5 g**	Larger g-levels require high rotation rates and/or large diameters that are not flight-safe
Stowed Size	**30 cm × 30 cm × 15 cm**	The station must fold/collapse to fit in a standard carry-on size for transport.
Tether	**Flexible or Semi-Rigid**	Must allow smooth rotation without tangling. Twist-free swivels are encouraged.
COM Ring	**Required**	The tether must have a specific "Center of Mass Ring" or loop that fits over the turntable spindle.

Table 1. Key model station design requirements.

3.1 Materials

- **Allowed:** 3D printed plastics (PLA, ABS, CF, PETG, Nylon), cardboard, standard metal hardware (screws, washers), string/paracord.
- **Prohibited:** Lead weights, glass or brittle ceramics (shatter hazard), grains/liquids, or any sharp edges that could cut a tether or a person.

3.2 Safety Guidelines

Safety is the primary gate for this competition. If a design is deemed unsafe, it will not be scored.

- **Stable Balance:** The Center of Mass must be clearly identified and aligned with the rotation axis. Unbalanced loads cause dangerous wobbling.
- **Secure Attachments:** All modules and weights must be mechanically secured. Tape alone is not a structural fastener.
- **Safe Zone:** Observers must maintain a safe distance during spin testing.
- **Safe-Grasp Zone**: The Safe-Grasp Zone is a designated area on the station where operators can safely hold or stop the rotating assembly without risk of contact with moving tethers or modules. Teams can implement a safe-grasp zone as a short section of rigid tube that passes through the COM ring and which allows the COM ring to rotate smoothly around its circumference.

4 What Students Will Build

Participants will design, construct, and demonstrate a rotating "artificial gravity" space station inspired by the station described in *Project Hail Mary*. Each team will build a physical model consisting of two modules (typically a Crew Compartment and a Propulsion Module) connected by a tether or structural element of length *L*. The two modules must have **unequal masses**, a requirement that ensures the system's center of mass (COM) does not lie at the geometric midpoint.

Figure 1. Braedon demonstrates a 3D print of the crew (L) and propulsion (R) modules as described in the Project Hail Mary book.

When the completed station is mounted on a horizontal turntable and spun about its COM, each module travels in a circular path. This motion requires each module to accelerate inward, which occupants inside would feel as an outward push against the floor—the sensation of artificial gravity. The two modules are at different distances from the COM, hence they experience different levels of artificial gravity, a characteristic feature of the station described in the novel.

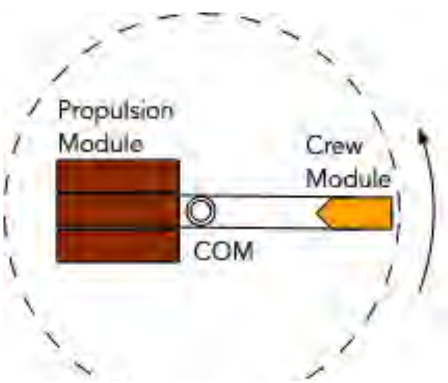

Figure 2. The proposed configuration consists of the two modules rotating about their center of mass.

Teams will choose a target artificial gravity level (up to 0.5 g) and design their station to achieve that level through a combination of mass selection, tether length, and rotation rate. Division II teams will use predictions and experiment to determine an appropriate rotation rate before testing; Division I teams may simply measure or estimate the level of gravity from their design.

The completed design must satisfy the mass limits, station ¨ameter limits, rotation-rate limits, and safety guidelines ·fined in Table 1. Each team will document its work rough CAD models, drawings, and measurements ·monstrating how the design performs during rotation.

The designs should draw their inspiration from the Project Hail Mary text, but do not need to align perfectly with the spacecraft described in the book. Creative interpretation, functional improvements, or narrative-based additions are encouraged and rewarded by the evaluation rubric.

Note that many teams will elect to use existing models of the Hail Mary ship available online (Figure 1). There are several freely available printable variants of the HM that can be lightly modified for use in this competition. Teams choosing to use prebuilt designs should clearly identify the source of their design. The models should be (1) scaled to sizes appropriate for this competition, and (2) adapted to securely dock to a Databot 2.0 (a portable multi-sensor accelerometer; see Appendix B) or equivalent sensor, for teams choosing the accelerometer-based measurement pathway. Teams without access to a Databot may use the turntable timing method described in Appendix A.

5 Competition Divisions

The Project Hail Mary Challenge is organized into two divisions to ensure that students engage with the competition at a level appropriate to their background while still participating in the same overall design mission.

Division I: K–8 Grades

Division I is open to all K–8 classrooms. The handbook procedures are written for middle school readiness; teachers of younger students should adapt activities as appropriate for their grade level.

Division I teams focus on conceptual understanding, physical intuition, and hands-on measurement. Teams are *not* required to use formal rotational mechanics or perform algebraic calculations. Emphasis is on creative interpretation of *Project Hail Mary*, clear communication of design choices, and demonstration that the station behaves as intended. See Section 6 for specific learning objectives.

Division II: High School

Division II teams complete the same design challenge with additional analytical expectations. Teams must compute the center of mass mathematically, predict required rotation rates for their chosen gravity level, and validate predictions against measurements. Prior coursework in rotational motion is not assumed; Appendices A and B provide step-by-step procedures and the necessary physics background for both teachers and students.

What's the Same Across Divisions

Both divisions:

- Design and build a two-module, tethered rotating station
- Determine the center of mass and install a COM ring
- Rotate the station and measure artificial gravity
- Submit the same deliverables (CAD model, drawings, narrative, videos, mission patch)
- Are evaluated using rubrics with identical categories and weights (Section 8)

The difference lies in *how* teams approach measurement and analysis, not in *what* they build. Detailed learning objectives for each division appear in Section 6, with full measurement procedures in Appendices A and B.

6 Summary of Objectives

Across both divisions, students will design, build, and test a rotating space station model inspired by *Project Hail Mary*. Each team engages with core ideas in engineering design, measurement, and artificial gravity, with expectations scaled appropriately for Division I and II teams.

6.1 Learning Objectives

Division I Students Will Learn:

- How unequal masses connected by a tether rotate around a shared balance point (center of mass).
- How to determine the center of mass using a simple hands-on balancing method.
- How rotation can create "artificial gravity" and how to measure it using either a turntable setup or a Databot 2.0 accelerometer.
- How changing the rotation rate affects the artificial gravity level.
- How to communicate a design using basic drawings and measured dimensions.

Division II Students Will Learn:

- How to compute the center of mass using mass measurements and the one-dimensional COM formula.
- How to predict the required angular speed and rotation period to generate a chosen artificial gravity level (centripetal acceleration directed inward toward the center of mass).
- How to validate predictions using turntable timing, Databot acceleration measurements, or both.
- How to compare theoretical predictions with experimental measurements and evaluate agreement.
- How unequal mass distribution influences rotational dynamics and station behavior.
- How to communicate engineering designs through professional-quality CAD models and annotated drawings.

Detailed measurement and testing procedures for each division are provided in Appendices A and B.

6.2 Challenge Objectives

All teams pursue the same core objectives:

- **Design a two-module space station** connected by a tether or structural element, with intentionally *unequal* masses.
- **Determine the rotation point** (center of mass) so the system can spin smoothly.
- **Build a physical model** that can be rotated on a horizontal turntable or similar platform.
- **Generate and measure artificial gravity** at the crew module end of the station.
- **Document the design** through both CAD models and engineering drawings.

- **Communicate results** clearly, showing how their design choices influence the artificial gravity produced.

These objectives are the same for both divisions, but the level of analysis, mathematical modeling, and measurement detail differs by grade level. The evaluation rubrics for Division I and II teams are described in Section 8.

7 Submission Requirements

A complete submission consists of digital files uploaded to the competition portal. Each entry must include the required components listed below. Submissions that do not include all items cannot be considered for selection.

All proposals are submitted online using brief responses to web form prompts and file uploads at https://spaceforteachers.org/projecthailmary.

7.1 Required Deliverables

1. **Digital CAD Model:** A STEP (.stp) file of your full assembly.
2. **Engineering Drawing Set:** A PDF showing dimensions, views (Top, Front, Iso), and safety features.
3. **Class Narrative:** A PDF presentation (slides or document) telling the story of your design, testing, what you learned, and how the project was implemented in your school/classroom.
4. **Mission Patch:** A digital image (.png or .pdf) of your team's logo.
5. **Student Video (2-3 min):** Students explaining their design and safety features.
6. **Teacher Video (1-3 min):** A brief personal introduction from the teacher.
7. **Analysis Report (Division II Only):** A PDF documenting prediction and test results for your selected level of artificial gravity.

7.2 File Naming Convention

Please name your files exactly as follows (no spaces):

- TeamName_TeacherLastName_STEPmodel.stp
- TeamName_TeacherLastName_Drawings.pdf
- TeamName_TeacherLastName_Narrative.pdf
- TeamName_TeacherLastName_Patch.png
- TeamName_TeacherLastName_StudentVideo.mp4
- TeamName_TeacherLastName_TeacherVideo.mp4
- TeamName_TeacherLastName_Analysis.pdf (Division II only)

Videos must be submitted in MP4 format.

7.3 Digital Design Files

Each entry must include a clear digital representation of the proposed rotating space station *and* a corresponding PDF drawing set. These two components together allow judges to evaluate the physical feasibility, safety, and technical clarity of the proposed design.

7.3.1 Digital CAD Model

Teachers may use any CAD tool available in their classroom (Tinkercad, Onshape, Fusion 360, Inventor, SolidWorks, etc.) or another digital modeling tool if CAD is not available. To ensure judges can view all designs regardless of the software used, teams must submit:

1. A universal export file in STEP format (.stp or .step)
2. **The native CAD file** (optional)

The CAD model must show:

- The Crew Compartment
- The Propulsion Module
- The **tether** and approximate deployed length
- Approximate **radii** from the rotation center to each module
- The proposed Safe-Grasp Zone
- The tether attachment points and attachment mechanisms

The model must be sufficiently detailed to allow judges to check basic safety, size, and feasibility constraints. A 3D printer is **not required**; if your classroom does not have access to one, simply note this in the application.

7.3.2 PDF Engineering Drawing Set

Teams must submit a **PDF drawing package** generated from their CAD model. These drawings must allow judges to understand and evaluate the design **without opening the CAD files**.

Required Views

Each drawing set must include the standard engineering projections:

- Front view
- Top view
- Right-side view
- **Isometric view** (shaded or line drawing).

Additional views should be provided as needed, including:

- **Section views** showing internal features, attachment points, tether guides, Databot mount, etc.
- **Detail views** for small or critical features
- **Exploded assembly view** (recommended for more complex HS designs)

Required Dimensions

Drawings must include all dimensions (use mm) necessary to define the geometry of the station:

- Overall length between module centers
- Location of the **COM ring** relative to mass centers
- Tether length and attachment points
- Module dimensions (diameter, length, identifiable geometric features)
- Mounting details for Databot or other instrumentation
- Thicknesses, widths, and diameters of fabricated parts
- Relevant angles, radii, and offsets affecting balance or rotation

Dimensions must follow standard drawing conventions:

- Use **SI units** consistently
- Use proper dimension lines, extension lines, and leader lines
- Apply **tolerances** when relevant (e.g., ±1 mm for features impacting balance). Division I teams may omit formal tolerances if unfamiliar with this convention; focus on clear, readable dimensions.

Required Annotations
Drawings must include:

- A **title block** with team name, school, date, and page number
- The **scale** for each view (e.g., "Scale: 1:2")
- **Material callouts** for parts affecting mass (e.g., PLA, PETG, foam, PVC)
- **Mass estimates** for the two modules
    - Division I teams may provide approximate estimates
    - Division II teams should provide measured or calculated estimates
- Functional notes explaining key features (e.g., "COM ring aligns with spindle," "Databot +z axis inward," "Tether attachment reinforced")

7.3.3 Level of Detail Expected

Judges must be able to understand the full mechanical intent of the station **from the PDF drawings alone**. The drawing set must make it clear:

- How the station rotates about its true center of mass
- How the tether attaches and remains taut during rotation
- Where and how the Databot mounts (if used). Note that for the masses and rotation rates, Velcro is an adequate mounting strategy for the Databot.
- That the design meets size, mass, and safety constraints
- That the dimensions support the team's artificial-gravity goals

7.4 Class Narrative

Each team must submit a slide deck that documents the early thinking, reasoning, and exploratory testing behind the proposed station design. The document should capture the development process and lessons learned that led to the final product. Submit as a PDF (convert Google Slides or PowerPoint to PDF before submission).

The narrative should introduce the team's initial concept for a dual-gravity rotating station and explain, in clear language, how the mass distribution, tether length, and center-of-mass placement work together in the proposed design. Simple diagrams, sketches, early screenshots from CAD, and short written explanations are sufficient. The goal is to show how students used accessible physics ideas—including approximate radii, estimated rotation rates, and approximate artificial-gravity ranges—to justify the structure shown in their CAD model and drawing package.

Early testing activities should also be included. These tests do not need to resemble the final design and may involve simple classroom materials. Examples include spinning two masses on a string or rod, timing rotations with a stopwatch or video, or observing how changes in mass or radius affect rotation. Notes describing what students observed, how they interpreted those observations, and how these tests influenced the evolving design are an important part of the narrative. These tests help demonstrate that the design is grounded in evidence and reasoning, not guesswork.

The document should also reference the CAD model and PDF drawing set submitted, showing how the final digital geometry reflects what the students learned during exploration.

Photographs of completed modules and the assembled structure should be included to show the state of the station concept at the time of submission.

Overall, the purpose of the narrative is to demonstrate that the proposed station is physically reasonable, safe in concept, compliant with the challenge constraints, and developed through meaningful student engagement with math, physics, and engineering reasoning.

7.5 Mission Patch Design

Teams must submit a mission patch that represents their project. The patch should:

- Clearly connect to **Project Hail Mary**
- Reflect the idea of a rotating, dual-gravity station
- Include the **team or classroom name** and a short mission title or motto
- Communicate the team's mission story, values, and identity

Figure 2. Official Project Hail Mary mission patch.

Judges will assess how effectively the patch communicates the mission—not artistic skill or graphic-design sophistication.

7.6 Student-Led Video (2-3 Minutes)

Students must create a **2–3-minute** video introducing their design. The video must:

- Show the key features of the digital model
- Explain, in students' own words, how the **dual-gravity idea** works in their design
- Point out intended **safety features**, such as the Safe-Grasp Zone
- Describe how the team used math/physics reasoning and simple tests to check that the design is realistic and safe
- Include a brief statement about what students learned from connecting the project to *Project Hail Mary*

Teachers may support recording and logistics, but the explanation must come from students.

7.7 Teacher Video (1-3 Minutes)

Teachers must submit a brief (1–3 minute) introduction video. This is a personal introduction—there is no required format. Teachers may speak about:

- Their classroom and students
- Teaching philosophy
- Challenges and successes
- Why they wish to participate in the competition
- What excites them about bringing the Project Hail Mary challenge to their students

This video helps judges understand the educational context and the potential impact of the project.

8 Evaluation Criteria

All submissions are evaluated in two stages. First, teams must meet the **Feasibility Gate**, which ensures that the design can be safely built, rotated, and measured according to the rules of this competition. Only submissions that pass this initial gate proceed to full scoring.

Teams are evaluated using division-specific rubrics; both rubrics share the same categories and weights but differ in the depth of analysis expected.

8.1 Feasibility Gate (Required for Both Divisions)

Before scoring begins, judges verify that the submitted design is **safe, buildable, and compliant** with the rules in Section 3. A submission passes the Feasibility Gate if it demonstrates all of the following:

1. **Compliance with Physical Constraints**
   The model fits within the maximum diameter (1.0 m), mass limit (2.5 kg), stowed size requirement, and material restrictions.
2. **Valid Center-of-Mass Strategy**
   The submission shows a feasible method for identifying the true center of mass and includes a COM ring or equivalent feature placed at the correct location.

3. **Tether Integrity and Anti-Tangling Measures**
   The design describes a single tether (flexible or semi-rigid) that can remain taut and stable during rotation without twisting or knotting.
4. **Safe Mounting and Rotation Concept**
   The station can be mounted on a horizontal turntable, rotated below 40 RPM, and measured using the turntable or Databot method without presenting safety hazards.
5. **Measurement Feasibility**
   The design clearly supports one or both measurement pathways (turntable timing or Databot 2.0) described in Appendices A and B.

Submissions that fail the Feasibility Gate are not scored. Judges may provide feedback encouraging resubmission in future cycles.

8.2 Division I Scoring Rubric

The rubric emphasizes creativity, hands-on investigation, conceptual understanding, and broad student engagement. Precise calculations are not required; the focus is on reasoning, documentation, and classroom participation.

Scoring Note: Each rubric category is scored from 1 to 5 points, with weighted scores summed to produce a final score out of 100. The rubrics below provide anchor descriptions for 5 points (Excellence) and 1 point (Needs Improvement); scores of 2–4 reflect partial achievement between these anchors.

Category	Weight	Criteria for Excellence (5 pts)	Criteria for Needs Improvement (1 pt)
Technical Feasibility	**25%**	The design is clearly drawn (digital or hand-drawn) with measurements and labeled parts. Students explain how components fit together and remain within size and safety limits.	Drawings are unclear, missing labels, or incomplete. The design is oversized, unsafe, or impractical to construct.
Scientific Accuracy	**20%**	Students correctly describe that spinning creates artificial gravity—occupants feel pushed toward the floor (away from the center of rotation)—and attempt simple speed or g-level estimates. They understand how tether length and rotation relate.	Physics explanations are incorrect or unrelated (e.g., confusing rotation speed with gravity level, or misidentifying the center of mass). Students make no attempt to use the simple math provided.
Testing & Safety	**15%**	Students describe a safe method for spinning and measuring the station—such as using a barrier, wearing goggles, or stabilizing the setup. They	The testing plan involves unsafe practices (e.g., spinning by hand) or does not mention protective measures.

Category	Weight	Criteria for Excellence (5 pts)	Criteria for Needs Improvement (1 pt)
		clearly identify what they intend to measure.	
Student Engagement	**10%**	All students contribute to the project and can explain what they learned. The work clearly reflects student ownership and participation.	Work appears to have been completed by only one or two students or built primarily by an adult. Students cannot explain the design.
Community Outreach	**10%**	Students share their project with others (another class, school event, library display, etc.) in age-appropriate ways that communicate what they learned.	No plan to share the project beyond the immediate team.
Aesthetic Design	**10%**	The station is visually creative and shows effort. The Mission Patch is colorful, meaningful, and connected to the mission story.	The station looks unfinished or generic. The Mission Patch is missing or low-effort.
Presentation	**10%**	The written summary is clear and easy to follow. The video is enthusiastic, audible, and tells a coherent story about the mission. Submission guidelines are followed.	Writing is unclear or extremely brief. The video is hard to hear, disorganized, or missing.

8.3 Division II Scoring Rubric

The rubric includes the same categories and weights as the Division I rubric but evaluates deeper analytical reasoning, correct application of physics, and the ability to compare predictions with measurements.

Category	Weight	Criteria for Excellence (5 pts)	Criteria for Needs Improvement (1 pt)
Technical Feasibility	**25%**	The design is presented with professional-quality CAD or orthographic drawings, including dimensions and a realistic mass budget. Deployment mechanics are clearly workable, and safety factors ($\geq 2\times$ expected loads) are identified and justified.	The design violates constraints or appears impossible to build. Drawings are incomplete or missing dimensions. No mass estimates or safety considerations are provided.
Scientific Accuracy	**20%**	Calculations for rotation rate, g-level, and COM placement are correct, clearly shown, and based on appropriate physics (e.g., $a =$	Calculations are missing, incorrect, or based on guesses. Explanations confuse rotation with gravity or omit the

Category	Weight	Criteria for Excellence (5 pts)	Criteria for Needs Improvement (1 pt)
		$\omega^2 r$). The submission demonstrates strong understanding of rotational motion.	physics relationships required for HS submissions.
Testing & Safety	**15%**	The testing plan is detailed and feasible, with clear measurement strategies (turntable timing or accelerometer). Risks such as detachment or tether behavior are identified alongside specific mitigations and safety measures.	The plan lacks detail, fails to identify hazards, or does not include a clear method for obtaining data. Safety considerations are absent or unrealistic.
Student Engagement	**10%**	Student roles are clearly defined, and the work shows meaningful student leadership, iteration, and ownership. The project integrates well with curriculum or STEM goals.	The project appears teacher-driven. Student roles are unclear, and there is little evidence of meaningful student participation or learning.
Community Outreach	**10%**	The team shares its project beyond the classroom (e.g., mentorship activities, public demonstrations, family or community events) with the intent to inspire others in STEAM.	No outreach is attempted. The project remains entirely within the submitting classroom.
Aesthetic Design	**10%**	The station and Mission Patch are creative, coherent, and visually aligned with Project *Hail Mary*. Visual identity supports both mission theme and technical intent.	The station is plain or unfinished, and the Mission Patch is missing or low-effort with no mission theme.
Presentation	**10%**	The written summary is clear and technically polished, and the video is organized, audible, and persuasive. All submission requirements are followed precisely.	The writing or video is unclear, incomplete, or poorly structured. Submission guidelines are not followed.

9 Useful Introductory Tutorials

These work well for students who have not yet seen formal kinematics but can reason graphically and with proportionality. Appropriate for grades 6-8.

1. PhET: "Ladybug Revolution" (Rotation)
   - Interactive sim where a ladybug rides a rotating platform; students can change radius, angular velocity, show velocity/acceleration vectors, and graph them. PhET.
   - Very close to what you need: "spin a thing, feel a push outward," relate radius and spin rate to "how strong it feels."
   - Comes with teacher activities and is accessible down to late middle school.
   - Use in PHM context: Have students treat the ladybug as "the astronaut in the crew module." Ask: "What happens to the 'artificial gravity' at the bug when we move it farther from the center or spin faster?"

2. NASA "Real World: Centripetal Force" (ISS video + activities)
   - NASA video and associated activities on centripetal force, with grade 6–8 and 9–12 segments. NASA Science
   - Includes classroom activities and math tasks asking whether sci-fi artificial gravity is plausible. This video is particularly relevant to the PHM Challenge .
   - Use in PHM context: This is a good on-ramp: "Why can spinning create a gravity-like effect?" before you talk about tethered stations.

3. PBS Learning Media: "Rotations in Space"
   - Interactive activity adapted from NASA about how different objects rotate in space and what causes rotation. PBS Learning Media
   - Good for building intuition that a rigid body can spin around different axes and that distribution of mass matters.
   - Use in PHM context: Helps students understand why mass distribution matters—connecting to why unequal-mass modules rotate around the center of mass, not the geometric center.

4. Khan Academy: Centripetal Acceleration
   - Video lessons and practice problems covering centripetal acceleration, angular velocity, and the relationships used in Appendix B. Khan Academy.
   - Use in PHM context: Division II teams can use these lessons to understand the derivation behind $a = \omega^2 r$ and practice predicting rotation rates for target gravity levels.

10 Appendix A: Measurement and Testing Overview

10.1 Demonstrating Artificial Gravity with a Horizontal Spin Rig

Once the station model is built, teams will test how much artificial gravity it produces by rotating it about its center of mass. Teams may choose from two primary measurement pathways:

Turntable Timing Method
Teams rotate their station on a horizontal turntable and measure how long the system takes to complete each revolution. From the rotation period, they can determine the effective artificial gravity at the crew module. Middle School teams rely on direct measurement; High School teams use both predictions and measurements.

Figure 3. Commercially available lab turntable.

Lab turntables (Figure 4) are a common element of high school and college physics labs, but may not be readily available in the middle school classroom. Alternatives include a Lazy Susan, a swivel office chair base, or any other piece of equipment with a central spindle and a rotating platform.

Databot Accelerometer Method
Teams mount a Databot 2.0 sensor on the crew module, aligning its +z axis inward toward the center of mass. During rotation, the Databot, shown in Figure 5, records the inward (radial) acceleration. Middle School teams use this as a direct reading of artificial gravity; High School teams compare it to predictions from their design calculations.

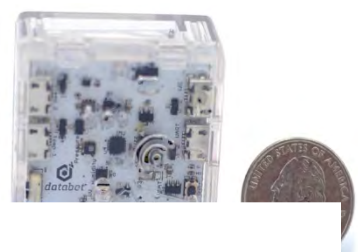

Figure 4. Databot 2.0. has dimensions 42.5 mm x 42.5 mm x 19 mm. The unit has a mass of 34 grams.

Both pathways allow teams to explore how artificial gravity depends on mass distribution, tether length, and spin rate. Detailed procedures for each method appear in the Appendices.

10.2 Objective

Demonstrate, using only video and stopwatches, that a rotating station model with unequal end masses connected by a flexible double tether[2] produces the predicted centripetal (artificial gravity) acceleration at the crew module when the system is rotated about its center of mass (COM), which is not at the geometric center.

[2] A **double tether** consists of two parallel cords or a single cord looped through the COM ring, ensuring the masses remain aligned during rotation and preventing twist accumulation.

The design prediction for the artificial gravity at the crew module is (High School/Division II content):

$$a_{\text{target}} = \omega^2 r_{\text{crew}} = \left(\frac{2\pi}{T_{\text{target}}}\right)^2 r_{\text{crew}},$$

where

- ω is the angular speed of the station about its COM,
- T_{target} is the corresponding rotation period,
- r_{crew} is the distance from the COM to the crew module, not to the geometric midpoint.

By rotating the model in a horizontal plane (spin axis vertical), real gravity acts vertically downward, while the artificial gravity of interest is purely horizontal.

10.3 Grade-Level Framing:

10.3.1 Division I (suited for middle school)

Learning goal: Develop an intuitive understanding that

- the two spacecraft sections have unequal masses,
- the system spins around a special balance point called the *center of mass* (COM),
- the artificial gravity depends on how far each section is from this balance point.

What Division I teams must do:

- Identify that one module is heavier than the other.
- Use a simple hands-on *balancing procedure* to find the COM:
  - Pull the tether straight.
  - Slide a finger or pencil under the tether until the two-mass system balances.
  - Mark this location as the spin point and install the COM ring there.
- Measure how long the model takes to spin once and use the provided artificial-gravity formula

  $$a = \omega^2 r$$

  with guided steps to estimate the acceleration a at the crew module.

What Division I teams are **not** required to do:

- No algebraic COM formula.
- No mass-weighted averages or torque calculations.

Division I teams operate primarily by measurement and balancing, not by derivation.

10.3.2 Division II (HS)

High school physics courses differ widely. Many students in algebra-based physics will not have seen rotational inertia, COM-based rotation, or multi-body rotational systems. This activity teaches the required formalism in context.
What HS students must do:

- Measure or estimate m_1 and m_2 and compute the COM using
$$x_{\text{COM}} = \frac{m_2}{m_1 + m_2} L.$$
- Install the COM ring at the calculated location along the tether.
- Use the correct radius
$$r_{\text{crew}} = |x_{\text{crew}} - x_{\text{COM}}|$$
from COM to crew module (not the geometric midpoint).
- Calculate and compare artificial gravity using
$$a = \omega^2 r_{\text{crew}}.$$
- Verify experimentally that spinning about the COM yields smooth rotation, while spinning about the midpoint produces wobble.

These steps mirror real engineering procedures for tethered spacecraft design. Prior exposure to rotational motion is not assumed.

10.4 Equipment

- Horizontal rotating platform ("spin rig") that can support the model, such as:
    - a lab turntable (e.g., standard physics-lab rotational platform),
    - a sturdy board (approximately 1.2 m × 0.10 m) mounted on a swivel base (swivel stool, office chair base, or a heavy-duty lazy Susan bearing).
    - See Figure 6 for a schematic of the apparatus.
- Physical model of the station consisting of:
    - two unequal masses, m_1 and m_2 (e.g., a crew module and a counter-mass),
    - a flexible *double tether* connecting the two masses so that, under rotation, they are pulled into a straight line.
- A small ring or short tube segment that can be attached to the tether and that will serve as the COM ring (the spindle of the rotation axis will pass through this ring).
- Measuring tape or ruler.
- Phone or tablet with video recording capability (30–60 fps is adequate).
- One or two stopwatches (or stopwatch apps on phones).
- Tape and marker for reference marks.

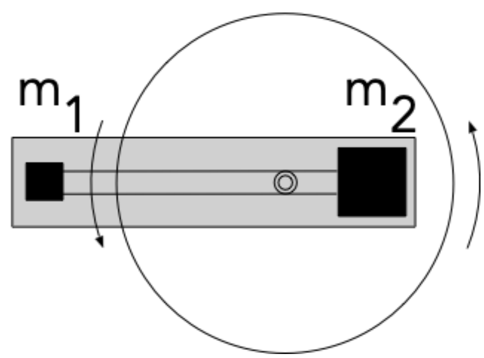

Figure 5. Schematic of the "spin rig" consisting of a turntable, spindle, and board for securing the station components. Note that the turntable spindle passes through the COM ring.

If a full 1 m-sized rig cannot be constructed, the system may be scaled down. The physics is identical as long as the distances to the COM are known.

10.5 Step 1 – Define the Tethered Unequal-Mass Station Model

Consider two end masses, m_1 and m_2, connected by a flexible double tether. Under rotation, the tether will be pulled taut, so the centers of m_1 and m_2 lie approximately on a straight line separated by a distance L.

- m_1: mass representing the crew module at one end of the tether,
- m_2: counter-mass or "propulsion" module at the other end,
- L: distance between the centers of m_1 and m_2 along the tether, when the tether is pulled straight.

The geometric midpoint would be at $L/2$, but the system must rotate about its *center of mass*, which, for unequal m_1 and m_2, is shifted toward the heavier mass.

10.6 Step 2 – Determine the Center of Mass (COM) for a Flexible Tether System

Even though the tether is flexible, the COM of the two-mass system lies somewhere along the line connecting the centers of m_1 and m_2 when the tether is taut. We (1) determine the separation and masses, (2) compute the COM (HS), and/or (3) locate it by balancing (MS), and (4) physically mark it with a COM ring.

10.6.1 Step 2A – Measure Masses and Separation

1. Lay the system on a table with the tether pulled straight between the two masses. Mark the center of each mass on the tether or on the table.
2. Measure the distance L between the two marks (center of m_1 to center of m_2).
3. Determine (or measure) the masses m_1 and m_2:
   - Preferred: Use a scale to weigh each module separately.
   - Alternate: If the modules are identical shells filled with different amounts of material, students can estimate masses from filling levels or use balance methods.

10.6.2 Step 2B (Div. II / HS formalism) – Compute the COM Position Along the Tether

Choose a coordinate x along the tether with $x = 0$ at the center of m_1 and $x = L$ at the center of m_2. The one-dimensional center-of-mass position is

$$x_{\text{COM}} = \frac{m_1 \cdot 0 + m_2 \cdot L}{m_1 + m_2} = \frac{m_2}{m_1 + m_2} L.$$

1. Compute x_{COM} using the formula above.
2. Measure the distance x_{COM} from the center of m_1 along the (straight) tether.
3. Mark this location on the tether as the **COM point**.

The distances from the COM to each mass (along the tether) are then

$$r_1 = x_{\text{COM}},$$
$$r_2 = L - x_{\text{COM}}.$$

If the crew module is at m_1, then
$$r_{\text{crew}} = r_1 = x_{\text{COM}}.$$
If the crew module is at m_2, then $r_{\text{crew}} = r_2$.

10.6.3 Step 2B (Div. I / MS version) – Locate the COM by Balancing

For middle-school teams, the COM may be found without formulas:

1. Pull the tether straight with both masses attached.
2. Slide a pencil or finger under the tether at different points until the system balances horizontally (neither end drops significantly).
3. Mark this balance point on the tether; this serves as the COM location for the activity.

This balancing method is less precise but sufficient for MS-level work and directly illustrates the physical meaning of COM.

10.6.4 Step 2C – Install a COM Ring on the Tether

To ensure that the physical rotation axis passes through the COM, install a small ring at the COM location on the tether.

1. Use a small rigid ring or a short segment of tubing that the tether can pass through.
2. Slide the ring along the tether until its center is at the COM mark (from either the HS computation or MS balancing).
3. Fix the ring in place (e.g., with small knots, clamps, or tape on either side) so that it does not slide during the experiment.

This **COM ring** is the point through which the spin rig's spindle will pass. When the system is rotated, the two masses will orbit this ring, and the ring itself will remain at the COM.

10.7 Step 3 – Determine the Target Rotation Period

Choose a target artificial gravity level at the *crew module*, such as $0.4g$.

1. Define the target artificial gravity at the crew module, for example
$$a_{\text{target}} = 0.4\,g \approx 0.4 \times 9.81\ \text{m/s}^2.$$
2. Let r_{crew} be the distance from the COM to the crew module (either r_1 or r_2, depending on which end hosts the crew module).
3. Compute the target angular speed:
$$\omega_{\text{target}} = \sqrt{\frac{a_{\text{target}}}{r_{\text{crew}}}}.$$
4. Convert this to a target rotation period:
$$T_{\text{target}} = \frac{2\pi}{\omega_{\text{target}}}.$$
5. Compute an easy reference such as the time for N revolutions (for example, $N = 10$):

$$t_{N,\text{target}} = N\,T_{\text{target}}.$$

Teachers may pre-compute these values and provide them to students if desired.

10.8 Step 4 – Set Up the Horizontal Spin Rig (Spindle Through the COM Ring)

1. Place the rotating platform (lab turntable or swivel-based board) so it can spin freely in the horizontal plane with a vertical rotation axis.
2. Mount the COM ring so that the spin rig's spindle passes through it:
   a. If the spindle is a vertical rod (lab turntable), place the COM ring over the rod so the tethered system is supported from the ring.
   b. If you are using a flat board with a marked rotation center, attach a short vertical pin or screw at the center and seat the COM ring over that pin.

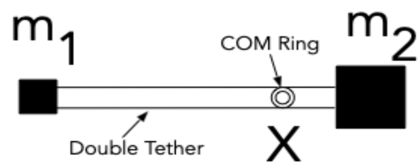

Figure 6. Schematic diagram showing crew and propulsion modules with a double tether and a COM ring for positioning the turntable spindle.

3. Ensure that:
   a. The COM ring lies exactly above the mechanical rotation axis of the rig.
   b. The tether is free to pull taut under rotation, forming a straight line from m_1 to m_2.
4. Mark the rotation axis on the board as "Rotation Axis (COM)."
5. When the tether is pulled straight (representing the configuration under spin), measure and record r_{crew} as the distance from the COM ring to the center of the crew module along the tether; this is the radius used in all $a = \omega^2 r$ calculations.
6. On the edge of the board (or on the table under it), mark a fixed "reference line" that can be observed as the crew module passes by once per revolution.

10.9 Step 5 – Camera Placement and Practice Spins

1. Position the camera:
   a. Ideally above the rig (on a tripod, ladder, or balcony) looking down so the motion is clearly in the horizontal plane.
   b. If a top-down view is not possible, use a side view but ensure the crew module path and the reference line are clearly visible.
2. Perform practice spins about the COM:
   a. Gently spin the rig until it rotates at a roughly steady speed and the tether is pulled taut.
   b. Observe how long it takes for the crew module to complete one revolution.
   c. Aim for a speed such that timing N revolutions takes on the order of 10–30 seconds; this improves timing accuracy.
3. (Optional conceptual demonstration): briefly spin the system with the spindle not aligned with the COM ring (e.g., using the geometric midpoint instead) to show the resulting wobble and precession, then contrast with the smooth motion when the spindle passes through the COM ring.

10.10 Step 6 – Data Collection (Video and Stopwatches)

Each trial measures the time for a known number of revolutions N (for example, $N = 10$).

1. Start the camera recording.
2. A student operator brings the rig up to a steady spin (with the tether taut and rotating about the COM ring) by hand.
3. A student timer stands where they can see the crew module passing the reference line.
4. As soon as the crew module crosses the reference line, the timer:
   a. Starts the stopwatch and calls out "Start!"
   b. Counts revolutions out loud: "1, 2, 3, …, N."
5. When the crew module passes the reference line for the N-th time, the timer:
   a. Stops the stopwatch and calls out "Stop!"
6. Record:
   a. N (the number of revolutions, e.g., 10),
   b. t_N (the measured total time from the stopwatch).
7. Continue recording video during the entire trial; the video is the primary record.

Repeat the measurement for at least three trials at nominally the same spin speed.
Optional: Timing Using Video Only
Instead of timing live with a stopwatch, students may:

- Mark on the video the frame where the crew module crosses the reference line for revolution 0 and revolution N.
- Use the video frame rate or time stamps to calculate t_N by frame counting.

This analysis can be done later using simple video tools.

10.11 Step 7 – Data Analysis

For each trial:

1. Compute the measured period per revolution:
$$T_{\text{meas}} = \frac{t_N}{N}.$$
2. Compute the measured angular speed:
$$\omega_{\text{meas}} = \frac{2\pi}{T_{\text{meas}}}.$$
3. Compute the measured centripetal acceleration at the crew module:
$$a_{\text{meas}} = \omega_{\text{meas}}^2 \, r_{\text{crew}},$$
where r_{crew} is the distance from the COM ring to the crew module along the tether.
4. Express a_{meas} in units of g:
$$\frac{a_{\text{meas}}}{g} = \frac{a_{\text{meas}}}{9.81}.$$

Average T_{meas}, ω_{meas}, and a_{meas} over all trials to obtain a best estimate.

10.12 Step 8 – Compare to Design Prediction

1. Compare the measured period to the target:
$$\text{Percent difference in } T = \frac{|T_{\text{meas}} - T_{\text{target}}|}{T_{\text{target}}} \times 100\%.$$
2. Compare the measured artificial gravity to the target:

$$\text{Percent difference in } a = \frac{|a_{\text{meas}} - a_{\text{target}}|}{a_{\text{target}}} \times 100\%.$$

3. Discuss:
   a. Whether the measured artificial gravity at the crew module is within an acceptable range of the design value.
   b. How uncertainty in timing, radius measurement, and steadiness of the spin affects the result.
   c. Why ensuring that the spindle passes through the COM ring (rather than the geometric midpoint) is essential for correctly predicting r_{crew} and $a = \omega^2 r$ in a tethered, unequal-mass system.

10.13 Notes and Variations

- **Scaling down:** If a full 1 m board is not available, use a shorter board and smaller L. Recalculate x_{COM} and r_{crew} for that geometry; the same analysis applies.
- **Two different accelerations:** Because $r_1 \neq r_2$, the two ends experience different centripetal accelerations:
  $$a_1 = \omega^2 r_1,$$
  $$a_2 = \omega^2 r_2.$$
  Advanced students can compute and compare a_1 and a_2 directly, and discuss implications for different gravity requirements at different ends.
- **Error analysis:** Students can estimate timing uncertainty (for example, ± 0.2 s on t_N) and propagate it to uncertainty in a_{meas} by standard error propagation methods.
- **Visualizing COM vs geometric center:** Have students mark both the geometric midpoint ($L/2$) and the computed or balanced COM on the tether, and explicitly compare motion when the spindle passes through the COM ring versus when it passes through the geometric midpoint. The wobble and precession in the latter case provide a clear demonstration of the importance of rotating about the COM in station design.

11 Appendix B: Turntable Testing with Databot 2.0

Measuring centripetal acceleration with Databot 2.0

11.1 Objective

Use a Databot 2.0 accelerometer mounted on a rotating, tethered station model with *unequal* end masses to:

- For **Division I** teams: *measure* the rotation rate needed to reach a chosen artificial gravity level (up to 0.5 g) at the crew module.
- For **Division II** teams: *validate* the predicted artificial gravity
$$a = \omega^2 r_{\text{crew}}$$
by comparing Databot measurements with the theoretical value based on their design calculations.

The station rotates in a horizontal plane (vertical spin axis), so true gravity is vertical and the measured radial component corresponds directly to the artificial gravity in the crew frame.

Databot 2.0 is used as a 3-axis accelerometer, with the $+z$ axis aligned along the *inward radial direction* (toward the center of mass), so that—when properly aligned and rotating at constant speed—the artificial gravity is captured primarily in the z-component.

11.2 Grade-Level Framing: MS vs HS

1. Division I

Learning goal:

- Understand that the station has two unequal masses connected by tethers.
- Discover that the system spins about a special balance point called the *center of mass* (COM).
- Use the Databot reading to tell whether the artificial gravity reached the target value.

What Division I teams must do:

- Choose a target artificial gravity level (e.g., $0.2g$, $0.4g$, up to $0.5g$).
- Find the COM by a simple balancing method and place a COM ring there.
- Mount the Databot on the crew module with $+z$ pointing radially inward.
- Spin the system and adjust the speed until the Databot a_z reading is close to the target g-
- level.

What Division I teams are *not* required to do:

- No algebraic COM formula.
- No detailed error analysis.
- No vector-component decomposition beyond using the z-component.

Many HS physics courses have not covered rotation about a COM or tethered multi-body systems. This activity includes the necessary formalism.

What HS teams must do:

- Measure or estimate m_1 and m_2, compute the COM, and set a COM ring.
- Choose a target artificial gravity level (up to $0.5g$) at the crew module.
- Predict the required angular speed ω and rotation period T using

$$a_{\text{target}} = \omega^2 r_{\text{crew}}, \quad \omega_{\text{target}} = \sqrt{\frac{a_{\text{target}}}{r_{\text{crew}}}}, \quad T_{\text{target}} = \frac{2\pi}{\omega_{\text{target}}}.$$

- Mount the Databot with $+z$ inward and compare the measured a_z with the predicted a_{target}.
- Determine the actual rotation rate ω_{meas} by one of several acceptable methods (stopwatch, video, turntable markings).

11.3 Equipment

- **Rotating platform (spin rig):**
  - Physics-lab turntable (preferred), or
  - A sturdy board (approximately 1.2 m × 0.10 m) mounted on a swivel base (swivel stool, office chair base, or heavy-duty lazy Susan).

- **Station model:**
  - Two unequal masses, m_1 and m_2 (crew module and counter-mass),
  - A flexible *double tether* connecting the masses, which will pull taut under rotation.
  - A fixture or mounting surface on the crew module for Databot 2.0, with known radial distance from COM.

- **COM ring:** small rigid ring or short tube segment that can be fixed on the tether and through which the spindle (or central pin) passes.
- Databot 2.0, with accelerometer enabled.
- Device with the Databot mobile app (phone or tablet) and Wi-Fi connection.
- Measuring tape or ruler.
- Stopwatch (or use phone stopwatch) and optionally a phone camera for video.
- Tape and markers for reference marks on the board and station.

11.4 Step 1 – Station Geometry and Target Artificial Gravity

11.4.1 1A. Define the Tethered Station

Two masses m_1 and m_2 are connected by a flexible double tether. Under rotation, the tether straightens and the separation between mass centers is L.

- m_1: crew module (Databot mounted here).
- m_2: counter-mass or second module.
- L: distance between centers of m_1 and m_2 along the straightened tether.

11.4.2 1B. Choose a Target Artificial Gravity

Teams may choose any artificial gravity level

$$0 < a_{\text{target}} \le 0.5g.$$

Examples (for reference):

$$0.1g = 0.1 \times 9.81 \approx 0.98 \text{ m/s}^2,$$
$$0.2g = 1.96 \text{ m/s}^2,$$
$$0.4g = 3.92 \text{ m/s}^2,$$
$$0.6g = 5.89 \text{ m/s}^2,$$
$$1.0g = 9.81 \text{ m/s}^2.$$

MS teams can think in terms of "$0.4g$" as "about 4 m/s^2" and use the app readings directly in g-units.

11.5 Step 2 – Determine the Center of Mass (COM) and Install COM Ring

11.5.1 2A. Measure Masses and Separation

2. Lay the system on a table; pull the tether straight between the two masses.
3. Mark the center of each mass on the tether or table.
4. Measure L, the distance between these two marks.
5. Determine m_1 and m_2:
    - Preferred: weigh each module with a scale.
    - Alternate: use relative filling levels or a balance.

11.5.2 2B (HS) – COM Calculation

Choose $x = 0$ at the center of m_1 and $x = L$ at the center of m_2. Then

$$x_{\text{COM}} = \frac{m_1 \cdot 0 + m_2 \cdot L}{m_1 + m_2} = \frac{m_2}{m_1 + m_2} L.$$

6. Compute x_{COM}.
7. Measure along the tether from m_1 by this distance and mark the COM point.

The distances from COM to each mass are

$$r_1 = x_{\text{COM}},$$
$$r_2 = L - x_{\text{COM}}.$$

If the crew module is at m_1, then $r_{\text{crew}} = r_1$; if at m_2, then $r_{\text{crew}} = r_2$.

11.5.3 2B (Middle School) – COM by Balancing

For MS teams:

8. Pull the tether straight, with both masses attached.
9. Slide a finger or pencil under the tether at different points until the system balances horizontally.
10. Mark this balance point on the tether; treat it as the COM.

11.5.4 2C. Install the COM Ring

11. Thread the tether lines through a small ring or tube.
12. Slide the ring until its center is at the COM mark.
13. Lock the ring in place with knots, clamps, or tape so it cannot slide along the tether.

This COM ring is the physical point where the station will be supported and rotated.

11.6 Step 3 – Databot Orientation and Mounting

11.6.1 3A. Define the Radial Directions

When the system spins about the COM ring:

- The direction pointing *outward* from the COM ring to the crew module is the *positive radial direction*.
- The direction pointing *inward*, from the crew module back toward the COM ring, is the *negative radial direction*.

We want the Databot $+z$ axis to point along the *negative radial direction* (inward).

11.6.2 3B. Mount and Align the Databot

14. Identify on the Databot case where the $+z$ axis is labeled (refer to Databot documentation or markings).
15. Design or use a mounting surface/fixture on the crew module such that:
    - The Databot sits securely and will not move during rotation.
    - The $+z$ axis points *toward the COM ring* (inward).
16. Ensure the Databot is approximately level relative to the local tangential plane to minimize vertical components in the reading.

When this is done correctly, under steady rotation the main acceleration component measured should be $a_z \approx a_{\text{radial}}$, corresponding to the effective artificial gravity at the crew module.

11.7 Step 4 – Databot App Setup and Sampling Choices

17. Connect the Databot 2.0 to the Databot mobile app over Wi-Fi.
18. Select the accelerometer sensor and ensure that:
    - The x, y, and z components are visible.
    - Units are displayed in g (preferred) or m/s^2 (either is acceptable).
19. Set the sampling rate:
    - Recommended: **10–20 Hz** for clear, low-noise traces.
    - Teams may use higher rates if desired, noting that noise may increase.
20. Verify that the app is set to *stream data in real time* and that recording can be started/stopped.

Teams may either:

- Export data later (e.g., CSV to Excel), or
- Capture screenshots or images of the acceleration-time graph for documentation.

11.8 Step 5 – Setup on the Horizontal Spin Rig

21. Place the turntable (or swivel-mounted board) on a level surface.
22. Align the COM ring with the mechanical rotation axis:
    - Lab turntable: seat the COM ring on the central spindle.
    - Board-based rig: attach a short vertical pin or screw at the center and place the COM ring over it.
23. Pull the tether taut so that the two masses lie approximately on opposite sides of the COM along a straight line.

24. Measure and record r_{crew} = distance from COM ring to Databot (crew module) along the tether.
25. On the board or surrounding surface, add a fixed reference mark for visual counting of revolutions.

11.9 Step 6 – Target Predictions (Especially for HS Teams)

For a chosen a_{target} at radius r_{crew}:

$$\omega_{\text{target}} = \sqrt{\frac{a_{\text{target}}}{r_{\text{crew}}}},$$

$$T_{\text{target}} = \frac{2\pi}{\omega_{\text{target}}}.$$

Example (HS):

- Suppose $a_{\text{target}} = 0.4g = 3.92\ \text{m/s}^2$ and $r_{\text{crew}} = 0.5$ m.
- Then

$$\omega_{\text{target}} = \sqrt{\frac{3.92}{0.5}} = \sqrt{7.84} \approx 2.80\ \text{rad/s}.$$

- The target period is

$$T_{\text{target}} = \frac{2\pi}{2.80} \approx 2.24\ \text{s per revolution.}$$

Teams may pre-compute similar values for their chosen a_{target} and r_{crew}.

11.10 Step 7 – Data Collection with Databot

Goal: collect $\approx$ 10 seconds of steady rotation data.

26. Start the Databot recording in the app.
27. Gently spin the turntable:
    - Increase speed until the tether is taut and the system rotates steadily about the COM.
    - Avoid large oscillations or wobble.
28. Once steady rotation is reached, maintain a roughly constant speed for about **10 seconds**.
29. During this plateau, MS teams focus on the magnitude of a_z; HS teams will later use both a_z and the observed rotation period.
30. After about 10 seconds of steady rotation, allow the system to slow and then stop the Databot recording.

Optionally, a stopwatch or video can be used simultaneously:

- Start the stopwatch when the crew module passes the reference mark and count N revolutions to measure T_{meas}.
- Or record video and later determine the period by frame counting or using time stamps.

11.11 Step 8 – Middle School Team Analysis

11.11.1 8A. Reading the Databot Plot

31. In the Databot app, view the acceleration vs time plot.

32. Identify the region where the rotation speed looks steady (nearly flat a_z).
33. Read the approximate value of a_z in g units (or convert from m/s^2).
34. Compare with the target:
    - If target is $0.4g$ and Databot shows ≈ 0.35–$0.45g$, you are close.
    - If far from target, adjust spin speed and repeat.

11.11.2 8B. Simple Success Criteria for MS

MS teams can answer:

- Did the measured Databot acceleration a_z come within a reasonable range of the target g-level?
- How did changing the spin speed change the measured artificial gravity?
- How did the position of the COM ring affect the radius and thus the artificial gravity?

11.12 Step 9 – High School Team Analysis

11.12.1 9A. Determine the Measured Rotation Rate

HS teams should determine the actual rotation rate ω_{meas} by at least one of the following:

- **Stopwatch method:**
    - Measure the time t_N for N complete revolutions during steady rotation.
    - Compute

$$T_{\text{meas}} = \frac{t_N}{N}, \quad \omega_{\text{meas}} = \frac{2\pi}{T_{\text{meas}}}.$$

- **Video method:**
    - Count frames or use time stamps between successive passes of the crew module past the reference mark.
    - Compute T_{meas} and ω_{meas} as above.
- **Turntable markings:**
    - If the turntable has angle markings, measure time for a specific angle, then infer angular speed.

All of these are acceptable; teams should document the method they used.

11.12.2 9B. Compare Databot Measurement with Theory

From the Databot a_z in the steady region, determine the measured artificial gravity:

$$a_{\text{Databot}} \approx a_z.$$

From the measured ω_{meas} and radius r_{crew}, compute the theoretical centripetal acceleration:

$$a_{\text{theory}} = \omega_{\text{meas}}^2 r_{\text{crew}}.$$

Compare:

$$\text{Percent difference (Databot vs theory)} = \frac{|a_{\text{Databot}} - a_{\text{theory}}|}{a_{\text{theory}}} \times 100\%,$$

$$\text{Percent difference (Databot vs target)} = \frac{|a_{\text{Databot}} - a_{\text{target}}|}{a_{\text{target}}} \times 100\%.$$

Teams should discuss whether these differences are reasonably small given:

- Human variations in spin rate,
- Limited time spent at perfectly steady rotation,
- Measurement uncertainty in r_{crew} and t_N.

11.13 Notes, Troubleshooting, and Extensions

11.13.1 Sampling and Signal Quality

- If the signal looks noisy at high sampling rates, reduce to ~ 10–20 Hz.
- Ensure Wi-Fi connection is stable during the recording.
- If the plateau is short, try to maintain steady rotation longer.

11.13.2 Alignment Issues

- If the Databot is not aligned with $+z$ inward, the radial acceleration will appear mixed across axes. For this activity, only a_z is expected to represent radial acceleration.
- If a_z changes sign during rotation, check orientation; $+z$ may be reversed relative to the intended direction.

11.13.3 COM vs Geometric Center

- If the spindle is placed through the geometric midpoint rather than through the COM ring, the motion will show wobble and varying acceleration.
- Spinning about the COM ring should produce smoother acceleration traces and more stable a_z plateaus.

11.14 Summary

- MS teams use Databot as a direct artificial-gravity meter: choose a target g-level, adjust spin, and read a_z.
- HS teams connect the Databot measurement to formal predictions using $a = \omega^2 r_{\text{crew}}$, and compare target, measured, and theoretical values.
- In both cases, correct rotation about the COM (via the COM ring) and correct Databot orientation ($+z$ inward) are central to obtaining meaningful data.