11 TO 12

Staying Afloat – Cargo Ships & Equilibrium

The experiment and calculations at the centre of this lesson enable students to apply their existing knowledge of force, torque and equilibrium to the context of cargo shipping and the stability of marine vessels.

CLASSROOM TIME REQUIRED

2 sessions of 50-60 minutes

LEARNING OBJECTIVES AND OUTCOMES

Students will:

- Explore the concept of equilibrium as it applies to boats and ships
- Demonstrate an effect of the relationship between mass and attractive force due to gravity
- Identify a situation involving the application of torque
- Examine the meaning and an application of rotational equilibrium
- Distinguish between list and loll in the context of ship design and loading

MATERIALS REQUIRED

- Video of a cargo ship being loaded
- Per group of 3 students (plus 1 set for demonstration):
    - Empty food can (398ml) with sharp edges removed
    - Tablespoon (15ml) measure or equivalent small scoop
    - Water tank (or other container) that can hold enough water to allow the food cans to be submerged
    - Approximately 200 g pearl barley. (Consider having some excess, just in case.)
    - Approximately 60 x 60 cm piece of aluminum foil
- Diagrams showing metacentre, centre of gravity and centre of buoyancy (see *Attachments* below)

TECHNOLOGY RESOURCES REQUIRED

Computer and projector or Smart Board for sharing video resources

TEACHER PREPARATION

- Students must have prior knowledge of force, torque and equilibrium.
- Ensure you have the required number of cans and water containers.

- Purchase and bring in 200 g of pearl barley per group of students.
- Fill the water tanks with sufficient water to allow the cans to be submerged.
- Set up computer and projector, or Smart Board, for showing video resources.

CRITICAL VOCABULARY (see Glossary for definitions)

Ballast	Force	Metacentre
Centre of buoyancy	Heel	Rotational equilibrium
Centre of gravity	List	Torque
Equilibrium	Loll	

LESSON DEVELOPMENT

Activity 1

- Review with the class the principles of force, torque and equilibrium.
- Review the concept of centroid and how it is calculated.

Activity 2

- Ask the students if they have ever been in a small boat or canoe. Have they noticed what happens as they move from side to side in the boat? What happens when they stand up?
- Ask if any of the students have ever been seasick? Have they been told that they should move to a lower deck to experience less movement? (Did they prefer to trade this off for fresh air higher up in the ship!?)
- Check whether students can explain what is happening when a vessel rolls in terms of force, torque and equilibrium?
- Divide the students into groups of 3 and have them sketch a free body diagram for the situation where a vessel is upright and stable in calm water. Then repeat for when a vessel is slightly off upright ('heeled'). Combine the class's thoughts into consensus diagrams on the board.
- Discuss with the class that boats have a characteristic shape that determines how they roll. (For example, a row boat is significantly different from a kayak; how does a canoe behave?)
    - Help the class to recognize that as they move on a vessel, they are affecting its centre of gravity and that this is particularly so when they stand up.
    - Encourage the class to identify that the vector of the buoyant force will pass through the centre of buoyancy and a point somewhere above it. This point can be considered to be fixed for small angles of heel (≤ 15°). The point is characteristic of the vessel and is called the 'metacentre'. (See the diagram in *Attachments* below.)

Activity 3

- Show the following video of a cargo ship being loaded. Do the students notice the care to ensure that the load is evenly placed and why this is so?

Activity 4: Experiment

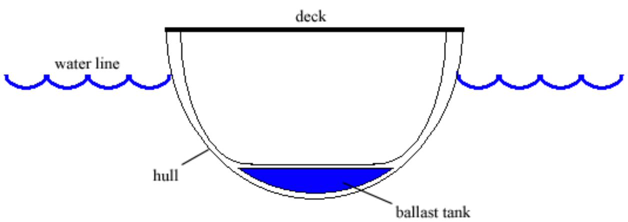
- Review Archimedes Principle
- In groups of 3, design a vessel that floats and can carry 200g of barley using aluminum foil:
    - What does the under water volume need to be to displace (200g of barley + mass of aluminum) of water?
    - Consider several shapes. See *Attachments* below for an image of a simple ‘coracle’ style, as one example.
- Review the stability of the different solutions developed by the students. Lead a discussion to identify which shapes are more stable. Guide the students to an understanding that the more stable shapes have a metacentre further above the centre of gravity.
- Have the students adjust the centre of gravity and shapes either to improve or worsen the stability. Notice that:
    - As the distance between metacentre and CG increases, the vessel is more stable
    - What is the effect of centering the barley? Levelling it?
    - What happens when the barley is off centre? (This is a “list”.)
    - Most vessels will be more stable with some barley in them than when empty. Can the students explain this in terms of metacentre and centre of gravity?

Activity 5: Calculations

- Explain that the class will now repeat Activity 4 for an idealized shape: a cylinder. This is to allow the class to make some useful calculations more easily than for the previously made shape. (Extension: attempt the calculations for their own shapes.)
- In their groups, have the students calculate:
    - The centre of gravity
        - For a general cylinder with both ends closed. Assume that the thickness of material is equal throughout. (Acknowledging but ignoring that this is not exactly true for the weld on the can)
        - Extension: For the slightly different location of centre of gravity when the top of the cylinder is open
    - The centre of buoyancy for the open cylinder floating upright
    - For the teacher’s convenience, the configuration is illustrated in *Attachments* below.
- Now, using simple geometry ask the students to calculate the centre of buoyancy using a small angle of heel (5° – 15°). Then, extending a vertical line through this centre of buoyancy to intersect with the centre line of the cylinder (which is the vertical line through the initial centre of buoyancy), have students identify the metacentre. Again, this is illustrated in *Attachments* below.
- Knowing the metacentre for the cylinder, have students consider it in the upright condition again. Is the previously calculated centre of gravity higher or lower than this metacentre?
    - And therefore what will happen to the cylinder when it is perturbed, even if sitting upright initially? (If necessary, guide the students back to the observation that the physics principles involved are non-aligned forces exerting a torque on the can, leading to angular motion.)
- Have students test their calculations and prediction with their empty can.

- Note that depending on the cans used, some may find a position of stability just before they fully capsize and others will not. It should be clear to the students that this is in line with their approximate calculations.

- Returning to the calculations: have students calculate, for the case of an upright can, how much barley needs to be added (if kept level) so that the centre of gravity is level with the metacentre?
  - Density of barley ~ 600 kg/m^3
  - Density of steel ~ 7800kg/m^3
- Have the students add their calculated mass of barley to their can in stages and observe the effect on stability.
  - With most but not all of the barley on board, the students may notice that the can will heel so that the centre of gravity drops to be level with the metacentre. In this position, the can has some stability. This is known as the Angle of Loll and is an important characteristic of a ship's design.
  - Adding more barley will right the can so that it can be significantly perturbed and will still return to vertical. Removing some barley will cause the loll to return. And re-adding the barley will return the can to upright.
- Extension: have the students consider ways in which this situation is managed in a large bulk cargo vessel where large masses of cargo are off loaded in port. They may need some encouragement to identify that water is often pumped on board into ballast tanks.
  - They may also have discussed in other subjects that this water can be a source of transfer of invasive species between countries and continents.



- Other observations:
  - If the barley is not level, with its top parallel to the base of the can, then the centre of gravity will no longer sit on the longitudinal axis of the vessel and the vessel will 'list'.

Activity 5: Recap

- Observe to the students that the can is like a ship that is badly designed.
- Have students consider that when a boat or canoe is designed and built, significant effort is put in to ensure that it sits level on the water. This is stable equilibrium. The design is created so that the net forces and torques are zero in this situation.
  - If you sit in a boat or canoe on one side, then it will list. Again, this is a result of gravity applying a force to your mass at a distance from the centre of the craft. This torque causes the craft to rotate. As the craft rotates, the buoyant forces will shift and (with luck and accommodating design) the torques will balance and the craft will establish a new equilibrium (and you will stay dry!).
- The students have observed that the centre of gravity and centre of buoyancy can be calculated. From these calculations, the metacentre of a vessel can be calculated and its stability predicted.
- These calculations can be complex and, while many vessel designs are traditional and based on generations of hard-won experience, for more advanced shapes, ships architects make the calculations

using computer aided design software. Whether calculated by hand, by computer, or not, the core principles that apply to vessel stability and safety are the same.

ASSESSMENT

Have students write up their experiment and calculations (from Activities 4 and 5) experiment using standard scientific method.

MODIFICATIONS

To reduce the number of resources required, the experiment may be conducted as a demonstration.

EXTENSIONS

- Use free-body diagrams and vector analyses to determine the sum of the forces acting at a single point on an object.
- The particularly engaged student may be interested in exploring another important factor in vessel stability and safety: shifting bulk cargo. This is known as the free surface effect. Refer to Transport Canada: The Free Surface Effect.

LESSON PLAN RESOURCES

- Video of a cargo ship being loaded
- Transport Canada: The Free Surface Effect

ADDITIONAL RESOURCES

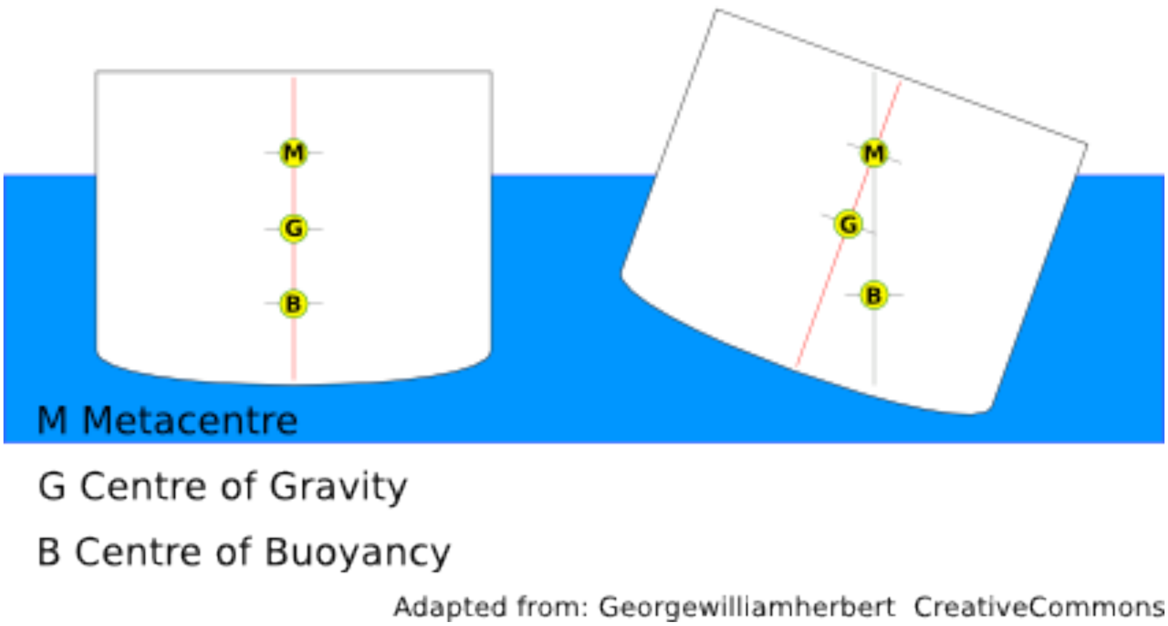
- A description of some problems associated with ballast water can be found on the Transport Canada website.
- Videos of a self-righting boats being tested:
  - Washington State
  - United Kingdom

  N.B. The Canadian Coast Guard also has self-righting boats but no video easily available.

ATTACHMENTS (below)

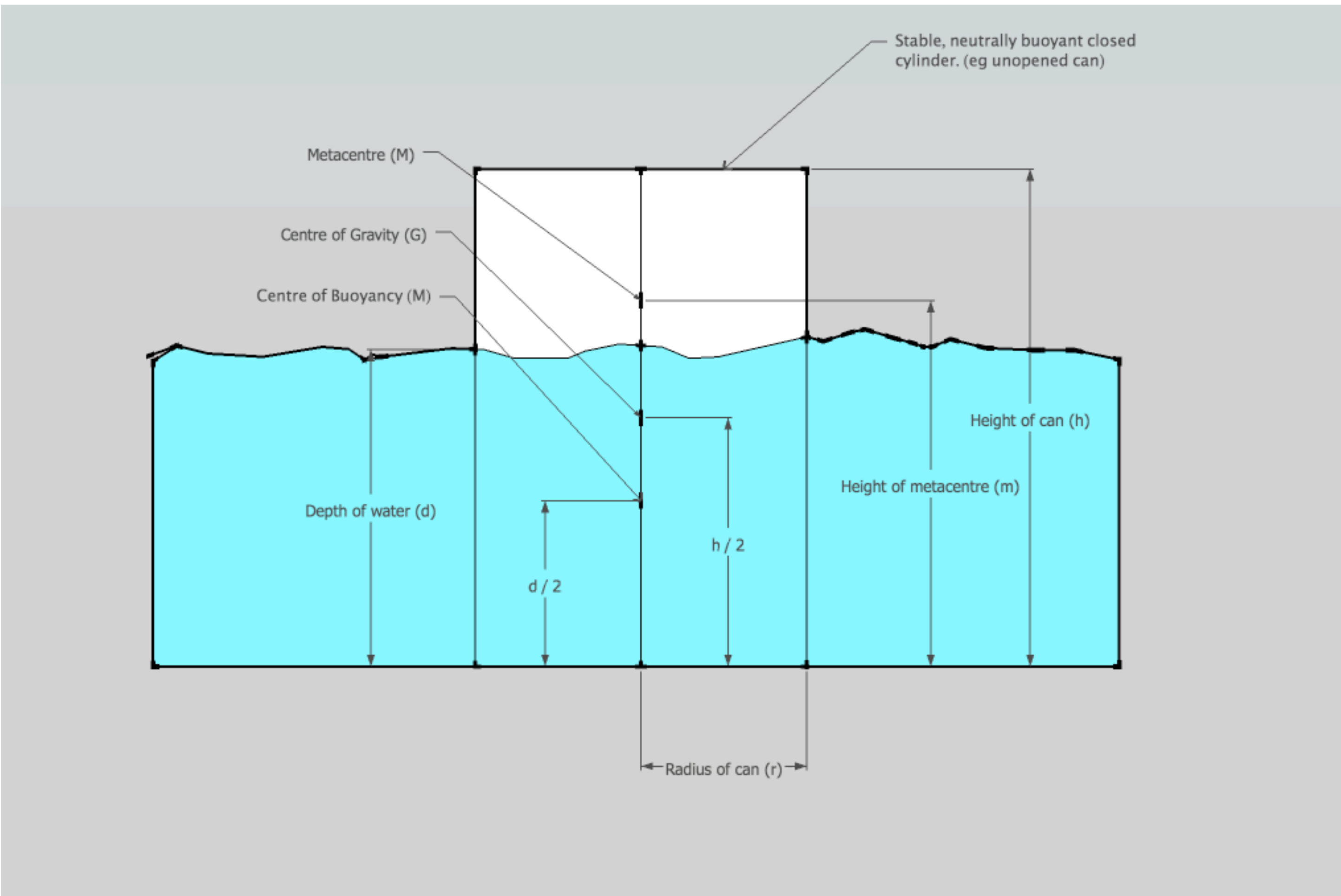
- Diagram showing metacentre, centre of gravity and centre of buoyancy
- Picture of a simple ‘coracle’ style vessel, made of aluminum foil
- Diagram showing calculated heights of metacentre, centre of gravity and centre of buoyancy for stable upright cylinder
- Diagram demonstrating identification of metacentre of a cylinder
- Diagram demonstrating different location of metacentre for narrower cylinder

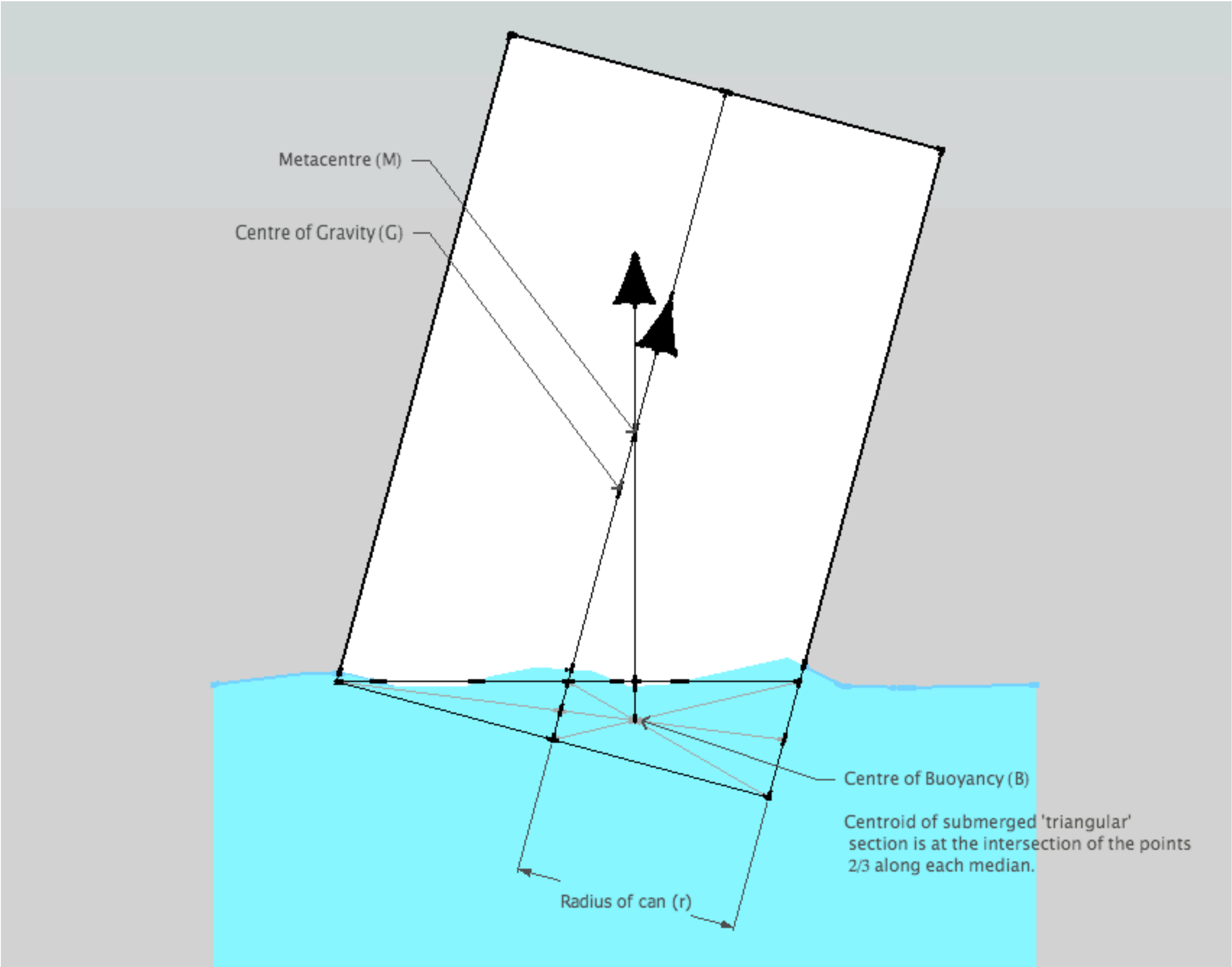
Metacentre, centre of gravity and centre of buoyancy



Aluminum foil 'coracle' style vessel

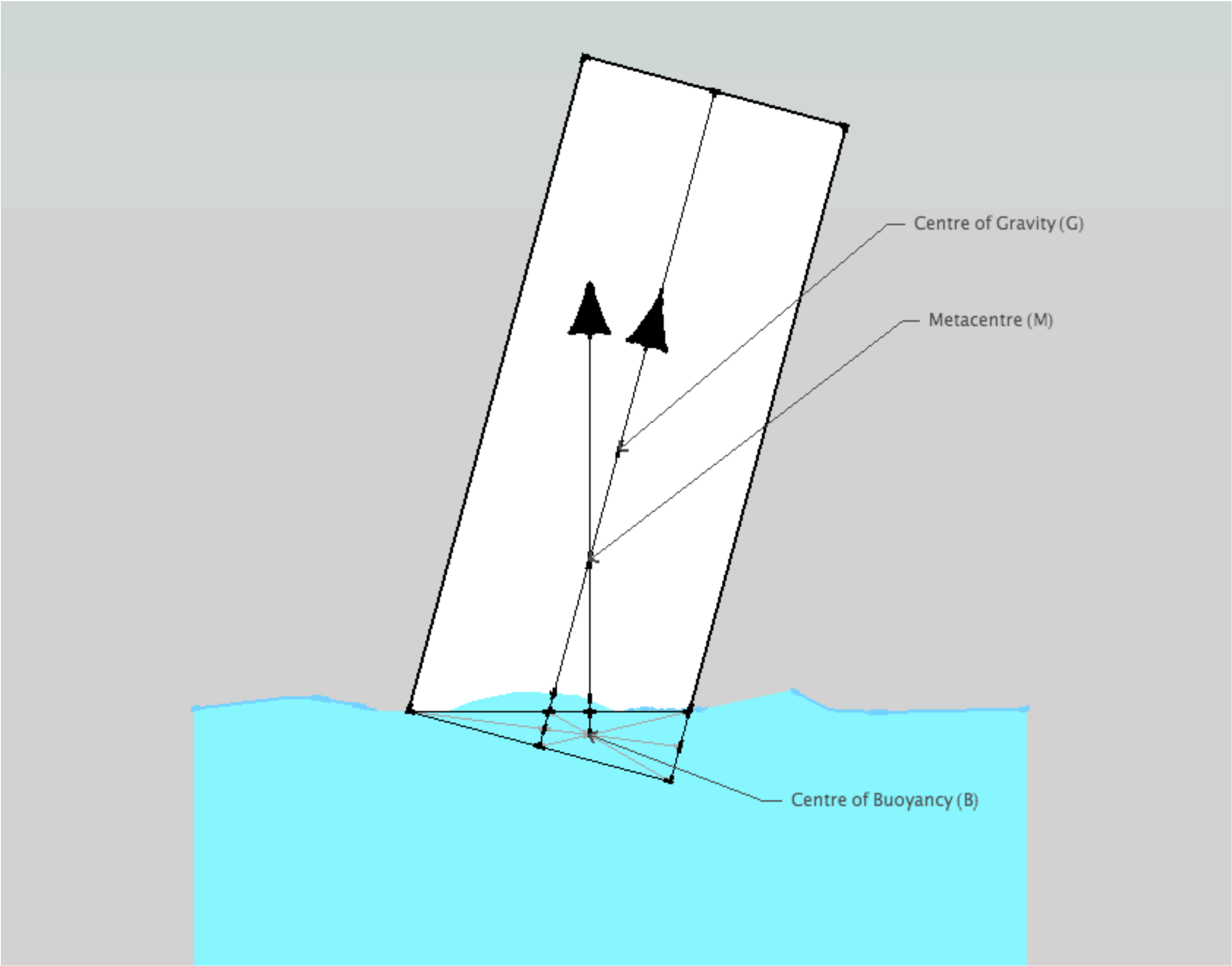
Example of simple foil vessel containing Barley


Stable, neutrally buoyant closed cylinder. (eg unopened can)
Metacentre (M)
Centre of Gravity (G)
Centre of Buoyancy (M)
Height of can (h)
Height of metacentre (m)
Depth of water (d)
h / 2
d / 2
Radius of can (r)



Location of metacentre can be shown geometrically for a known small angle of heel, using construction lines as shown.

Note: for this aspect ratio of can, the centre of gravity is below the metacentre and the can is stable.



For a narrower can, the metacentre can be shown to be below the centre of gravity.

The can is therefore not stable.