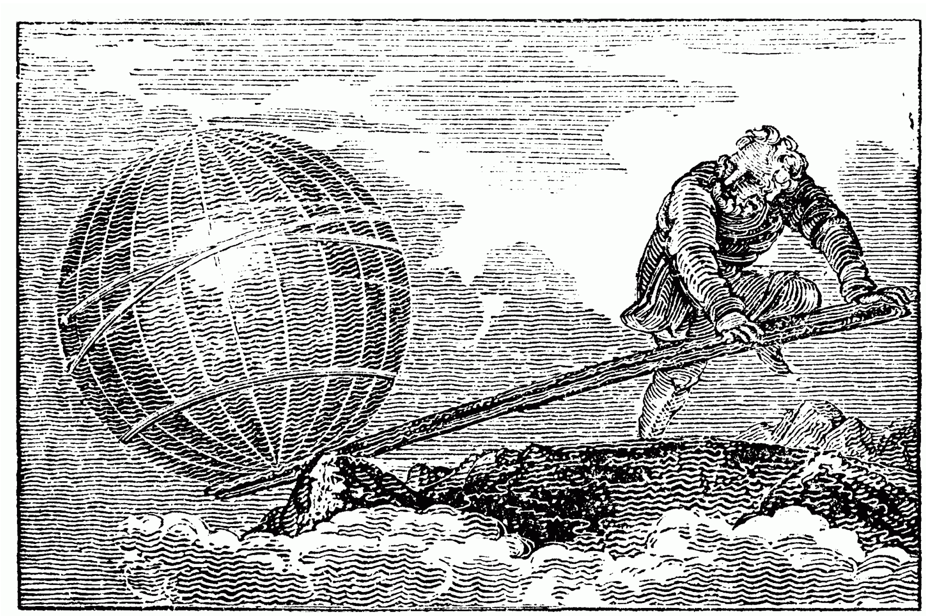
Science Olympiad
Machines C
Mira Loma Invitational

January 9, 2021



Directions:

- Each team will be given **50 minutes** to complete the test.
- There are two sections: **Section A** (Multiple Choice) and **Section B** (Free Response).
- Do not worry about significant figures. Just make sure to **use 3 or more in your answers**.
- Whenever needed, take the acceleration of gravity, g, to be $9.81\,\mathrm{m\,s^{-2}}$
- Tiebreakers, in order: Section B, §B3, §B2, §A1, . . . , §A30.
- Best of luck! And may the odds be ever in your favor.

Written by:

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Feedback? **Test Code**: *2021MLSO-MachinesC-Chain*

Section A: Multiple Choice

Each question in this section is worth two points, for a total of 60 points.

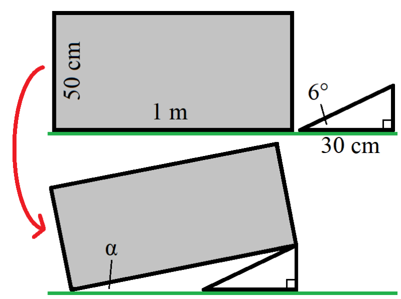
Questions 1-3 refer to the following scenario. Johnny is a building architect and is designing a handicap-accessible ramp to meet ADA standards. In order to count as a proper ramp, the ramp must have a 1:12 slope ratio (12 horizontal inches for each inch of vertical rise).

1. What is the IMA of an ADA standard ramp?
   A. 6.00
   B. 6.02
   C. 12.00
   D. 12.03
   E. 12.04

2. How much work must be done to push a 74.3 kg woman in a 15.9 kg wheelchair a distance of 10 m on the ramp? Assume no friction.
   A. 735 J
   B. 737 J
   C. 816 J
   D. 819 J
   E. 833 J

3. A man pushes a 17 kg box up the ramp and finds the ramp's efficiency is 45 %. What is the coefficient of kinetic friction?
   A. 0.10
   B. 0.15
   C. 0.20
   D. 0.25
   E. 0.30

Questions 4-8 refer to Nora the mason. Shown below is a 800 kg andesite slab with uniform density. She lifts the slab with a wedge such that the stone's edge meets the wedge's top edge.



4. What is the IMA of the wedge?
   A. 2.98
   B. 4.78
   C. 7.22
   D. 9.51
   E. 9.57

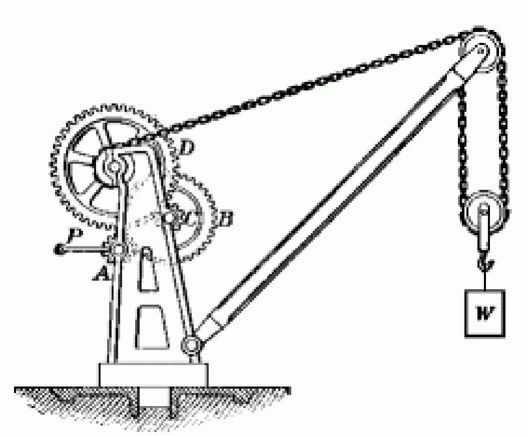
5. What is the minimum horizontal force Nora must apply to lift the stone when the wedge is just touching the stone? Assume the wedge is frictionless.
   A. 412 N
   B. 425 N
   C. 594 N
   D. 650 N
   E. 1440 N

6. How could Nora decrease the minimum force in the previous question?
   A. Increase wedge length and increase wedge height
   B. Increase wedge length and decrease wedge height
   C. Decrease wedge length and increase wedge height
   D. Decrease wedge length and decrease wedge height

7. What is angle α?
   A. 1.80°
   B. 1.81°
   C. 2.33°
   D. 2.34°
   E. 17.5°

8. What is the change in the stone's potential energy?
   A. 92 J
   B. −92 J
   C. 118 J
   D. −118 J
   E. 123 J

Questions 9-14 refer to Fitzgerald's crane, depicted below. All four gears are spur gears. Gears A and C have a radius of 10 cm. Gear B has a radius of 50 cm. Gear D has a radius of 60 cm and is connected to a pulley with a 20 cm diameter. The handle P has a length of 45 cm and the weight is 5000 N.



9. How many rotations must gear A make for gear D to make half a revolution?
   A. 80
   B. 60
   C. 30
   D. 15
   E. 5

10. If you want to lower the weight, what directions must gear A and D rotate in?
    A. A: counterclockwise, D: counterclockwise
    B. A: counterclockwise, D: clockwise
    C. A: clockwise, D: counterclockwise
    D. A: clockwise, D: clockwise

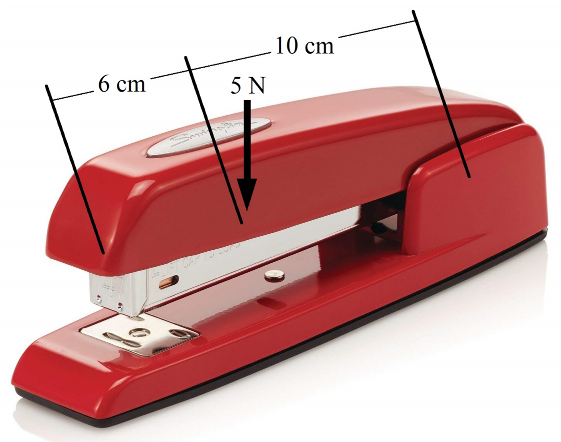
11. Currently, the weight is at rest. What is the tension in the chain?
    A. 1000 N
    B. 2500 N
    C. 3500 N
    D. 5000 N
    E. 8000 N

12. Assuming all components are frictionless, how much force must be applied at the end of the handle to lift the weight at a constant velocity?
    A. 4.63 N
    B. 6.91 N
    C. 18.5 N
    D. 37.0 N
    E. 74.1 N

13. If each fixed axle is 90 % efficient, what is the efficiency of the system?
    A. 80 - 90 %
    B. 70 - 80 %
    C. 60 - 70 %
    D. 50 - 60 %
    E. 40 - 50 %

14. To increase efficiency, Fitzgerald replaces the chain with a high-strength rope. Which of the following are possible benefits to this replacement? (Select all that apply)
    A. Lightens the machine.
    B. Adds torque complexity.
    C. Lowers AMA.
    D. Increases the cost of the crane.
    E. Reduces friction.

Questions 15-18 refer to Milton's red Swingline stapler, pictured below. The line on the right points to the hinge of the stapler and the arrow corresponds to 5 N of force applied where the line in the center points.



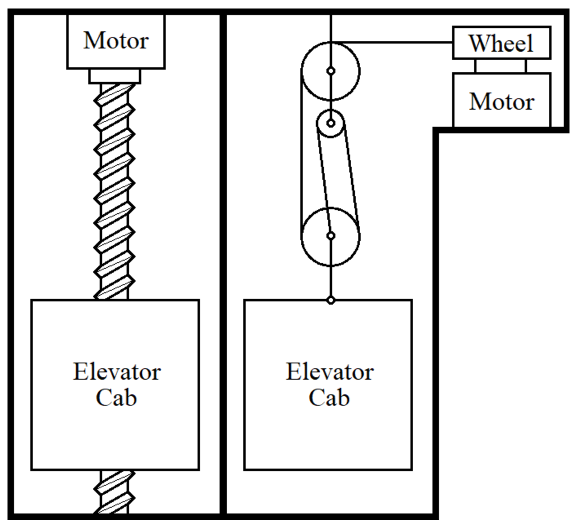
15. What class lever best describes the stapler arm?
    - A. Class 1 Lever
    - B. Class 2 Lever
    - C. Class 3 Lever
    - D. Class 4 Lever

16. What is the IMA of the stapler arm?
    - A. 0.38
    - B. 0.60
    - C. 0.63
    - D. 1.60
    - E. 1.67

17. The stapler arm is now completely pressed down and in equilibrium. What is the force exerted by the hinge onto the stapler arm?
    - A. 1.75 N
    - B. 1.88 N
    - C. 2.50 N
    - D. 3.13 N
    - E. 3.67 N

18. A standard 26/6 staple has a diameter of 0.405 mm and a leg length of 6 mm. What is the pressure at the staple's points of contact? Assume the staple legs are a perfect cylinder.
    - A. 3.03 MPa
    - B. 12.1 MPa
    - C. 19.4 MPa
    - D. 24.3 MPa
    - E. 48.5 MPa

Questions 19-26 refer to Janice's elevator. Currently, her elevator design is missing a lift mechanism. She is considering two options, shown below (not to scale): a pulley and a leadscrew system. Both systems are powered by motors.



19. What is the mechanical advantage of the pulley system?
    - A. 2
    - B. 3
    - C. 4
    - D. 5
    - E. 6

20. The motor in the pulley system is connected to a wheel with a 4 m diameter. If the motor rotates at 70 rpm, what is the speed of the elevator cab?
    A. $4.89\,\mathrm{m\,s^{-1}}$
    B. $3.41\,\mathrm{m\,s^{-1}}$
    C. $2.93\,\mathrm{m\,s^{-1}}$
    D. $2.51\,\mathrm{m\,s^{-1}}$
    E. $2.44\,\mathrm{m\,s^{-1}}$

21. The leadscrew is triple started with a 40 mm pitch and a 50 cm diameter. If the motor operates at 2400 rpm, what is the speed of the elevator cab?
    A. $9.50\,\mathrm{m\,s^{-1}}$
    B. $4.80\,\mathrm{m\,s^{-1}}$
    C. $2.67\,\mathrm{m\,s^{-1}}$
    D. $1.60\,\mathrm{m\,s^{-1}}$
    E. $1.33\,\mathrm{m\,s^{-1}}$

22. The leadscrew system has an AMA of 16. Assuming force is applied at the ends of the screw shaft diameter, what is the efficiency of the system?
    A. 20 %
    B. 40 %
    C. 60 %
    D. 80 %
    E. 100 %

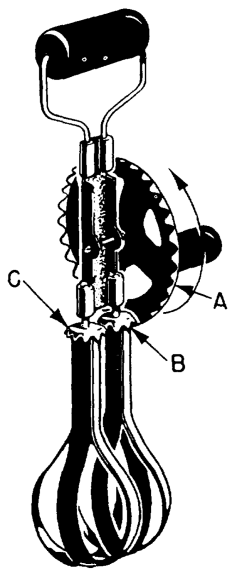
23. Janice wants to minimize the friction of the leadscrew. What type of thread should she use?
    A. Acme thread
    B. Buttress thread
    C. Unified thread
    D. Square thread
    E. Trapezoidal metric thread

24. What type of screw is the leadscrew and what direction should the motor rotate to lift the elevator (from the perspective of the passenger)?
    A. Right-handed, clockwise
    B. Right-handed, counterclockwise
    C. Left-handed, clockwise
    D. Left-handed, counterclockwise

25. Janice wants to **increase** the maximum capacity of the elevator. She decides to add a single-stage transmission to the motor. The transmission consists of two gears, a large one and a small one. Which gear should she connect the motor to and will the motor's output torque increase or decrease?
    A. Large, increase
    B. Large, decrease
    C. Small, increase
    D. Small, decrease

26. The single-stage transmission Janice uses has a 50-tooth gear and a 20-tooth gear. What is the **minimum** efficiency of the transmission (from the selection below) such that the maximum elevator capacity increases?
    A. 20 %
    B. 40 %
    C. 60 %
    D. 80 %
    E. 100 %

Questions 27-29 refer to Peter's eggbeater, depicted below. Gear A has 32 teeth and gears B and C have 8 teeth.



27. What type of gear is gear A?
    - A. Spur gear
    - B. Tooth gear
    - C. Gear rack
    - D. Crown gear
    - E. Bevel gear

28. If gear A rotates in the direction shown above, what is the rotation vector direction of gears B and C?
    - A. B: up; C: up
    - B. B: up; C: down
    - C. B: right; C: left
    - D. B: left; C: right
    - E. B: down; C: up

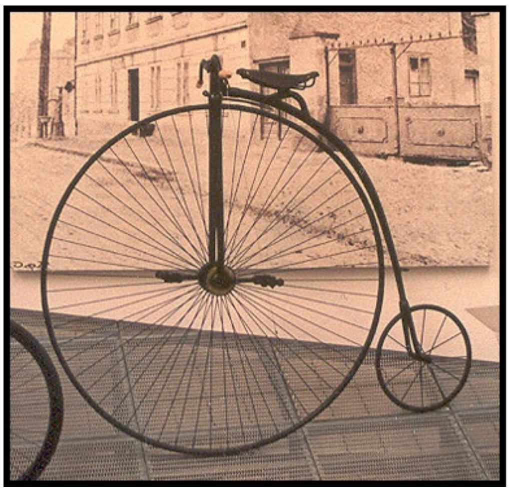
29. Gear A rotates at 100 rpm. What is the angular velocity of the whisks?
    - A. 800 rpm
    - B. 600 rpm
    - C. 400 rpm
    - D. 200 rpm
    - E. 50 rpm

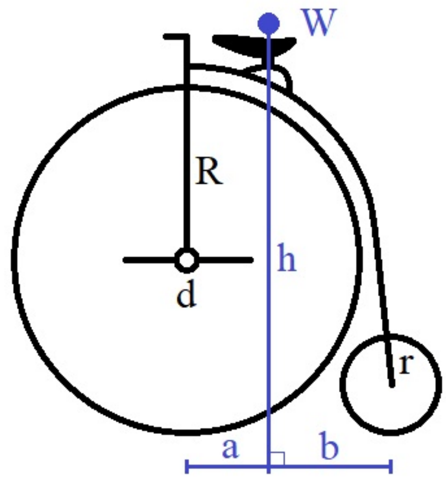
30. There are six non-reversible (the input and output **cannot** be switched) simple machines with IMAs of 2, 2, 3, 5, 5, and 7. How many possible unique IMA values can be made through the combinations of these six machines? Assume that using none of the machines results in an IMA of 1.
    - A. 1 to 15
    - B. 16 to 30
    - C. 31 to 50
    - D. 51 to 90
    - E. ≥ 91

Section B: Free Response

Points are shown for each question or sub-question, for a total of 90 points.

1. (18 points) Below is a picture and diagram of a penny-farthing, which was the first machine to be called a bicycle. It does not use a gear train, but rather is equipped with a large wheel to provide a mechanical advantage to its rider. The variables in the diagram are as follows: **R**, the radius of the large wheel; **r**, the radius of the small wheel; **d**, the distance between the pedals; **W**, the weight of the passenger; **h**, the minimum distance between the passenger's center of mass and the ground; and **a** and **b**, the distances from the point on the ground closest to the passenger's center of mass to the ground contact point of the large wheel and the small wheel, respectively.





(a) (1 point) What simple machine best describes the penny-farthing?

(b) (2 points) Give a possible reason for why the penny-farthing used such a large wheel.

(c) (15 points) The following questions will be answered in terms of the variables in the diagram.

i. (2 points) Calculate the IMA of the penny-farthing. Assume the system is ideal and massless.

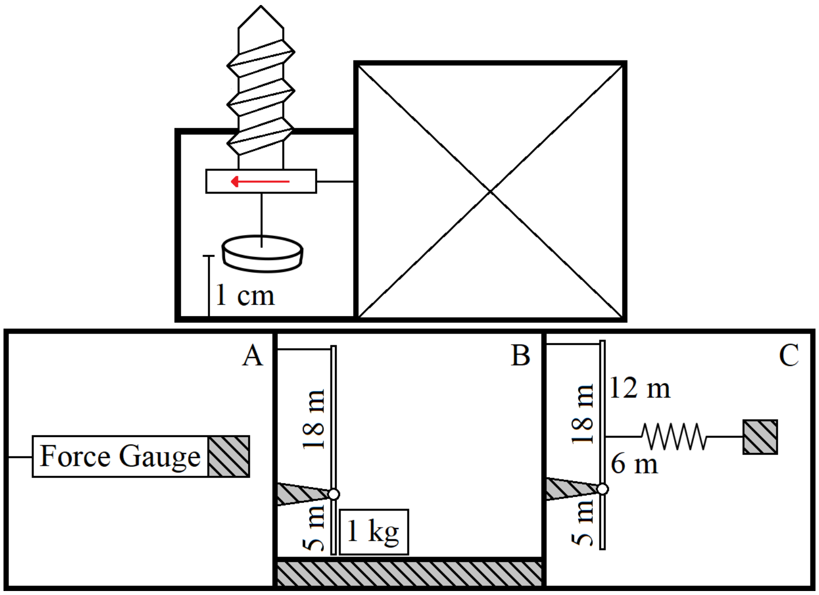
ii. (3 points) Let F_R and F_r represent the normal forces on the large and small wheel on level ground. Determine the equations that satisfy the equilibrium conditions.

iii. (3 points) Using the previous equations, solve for F_R and F_r.

iv. (3 points) Given c_l as the coefficient of rolling friction with dimension of length and F_{in} as the input force on the pedal. Find the AMA of the penny-farthing only in terms of R, d, W, c_l, and F_{in}. Simplify the expression given $2a = b$ and $R = 3r$. *(Use F_R and F_r for partial credit)*

v. (4 points) One downside of the penny-farthing is the precarious location of its center of mass. Riders often fall head-first if they go up or down too steep of an incline. Find the maximum angle of descent and maximum angle of ascent.

2. (30 points) Shown below is a diagram of the system (not to scale). A single-threaded screw of a 9 mm pitch, 2 mm shaft radius, and a 3 cm cap radius is fully embedded into the ceiling. A 2 kg disk is hung to the center of the screw, 1 cm off the ground. A cord is wrapped around the screw cap and connected to three setups at the bottom: A, B, and C. Assume all components are frictionless unless specified.



(a) (8 points) The cord is connected to a force gauge, shown in diagram A.

i. (2 points) Find the IMA of the screw. The input force is applied by the cord.

ii. (3 points) The force gauge measures a force of 1 N. What is the AMA of the system?

iii. (3 points) Calculate the screw's cap radius assuming the AMA is the IMA, in cm.

(b) (15 points) The cord is now disconnected from the force gauge and is connected to the end of a massless lever, acting as the effort force. At the end of the lever is a 1 kg block resting on a low friction surface ($\mu_k = 0.05$). The setup is shown in diagram B. *(Note: Use the IMA found in (a.i) for all calculations, not the force given in (a.ii).)*

i. (1 point) Identify the lever class.

ii. (1 point) Calculate the IMA of the lever.

iii. (3 points) The system is currently barely at rest. Find the coefficient of static friction (μ_s).

iv. (4 points) The block is nudged into motion. Determine the time it takes for the disk to reach the ground, in s. Assume tension is constant and the block and lever remains in contact over the entire interval.

v. (6 points) The block is nudged into motion. How far does the block travel, in cm? Make sure to include all assumptions made in your calculation.

(c) (7 points) The block is disconnected and the disk is raised back to its original position. A spring of spring constant $50\,\mathrm{N\,m^{-1}}$ is connected to the lever at a different position, shown in diagram C. *(Note: Use the IMA found in (a.i) for all calculations, not the force given in (a.ii).)*

i. (1 point) Identify the lever class.

ii. (3 points) The disk is now slowly lowered until the system is in equilibrium. How far is it lowered, in cm?

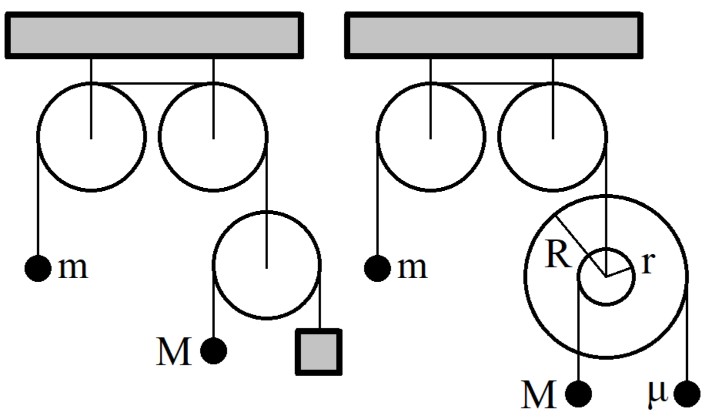
iii. (3 points) What if the setup was on the Moon? How far would the disk be lowered, in cm?

3. (30 points) As we cannot conduct the device testing portion of the event, you will draft up a design of a device. The device will follow the event and construction parameters and must be able to determine a mass ratio up to 10:1. However, it **must** consist of one **inclined plane** (the angle is adjustable) along with **one out of the two** following simple machines: one out the two (can only use one) or one out the two (must use two pulleys, fixed or moveable).
   (a) (1 point) Give a one sentence explanation of your device design.
   (b) (12 points) Draw two device diagrams.
      i. One diagram must be an isometric view of the device with labeled features.
      ii. One diagram must be a profile of the device with proper dimensions.
   (c) (10 points) Thoroughly explain the testing process for two mass ratios: 10:1 and 5:3. Each mass ratio explanation must include a profile diagram with the mass locations indicated and must work through the appropriate calculations.
   (d) (3 points) By using an inclined plane, the design faces the issue of self-locking. What coefficient of friction is required for your device to work for the largest mass ratio, 10:1. Show your work.
   (e) (4 points) Consider the following scenario:

After testing the device, you remove the masses, reset the device, and begin to pack it up. However, you notice the (lever begins/pulleys begin) to rotate on (its/their) own until (it comes/they come) to rest. You test this a few times and observe that (it/they) consistently (comes/come) to rest in the same position.

   Explain why this phenomenon occurs, how it would affect your mass ratio estimates, and provide a possible solution to remove or diminish it.

4. (12 points) Shown below on the left is a pulley system of two point masses (m and M) and three massless pulleys, one movable and two fixed pulleys, connected by ideal strings that move without slipping. The grey boxes are immovable surfaces.



   (a) (1 point) What is the IMA of the pulley system?
   (b) (3 points) If $m = 5\,\text{kg}$ and $M = 20\,\text{kg}$, find the direction and magnitude of acceleration for mass M, in $\text{m}\,\text{s}^{-2}$.

   The pulley system is modified. The movable pulley is switched with a coaxially connected ($r = 27\,\text{cm}$ and $R = 84\,\text{cm}$) one and a mass μ is added. The two mass-pulley pairs are connected by strings with fixed ends at the respective pulley. The new system is shown above on the right.

   (c) (3 points) If $m = 60\,\text{kg}$, find M and μ so that the system is in equilibrium, in kg.
   (d) (5 points) Find the tension in the string connected to mass μ, in N, when $M = 25\,\text{kg}$ and $\mu = 10\,\text{kg}$.