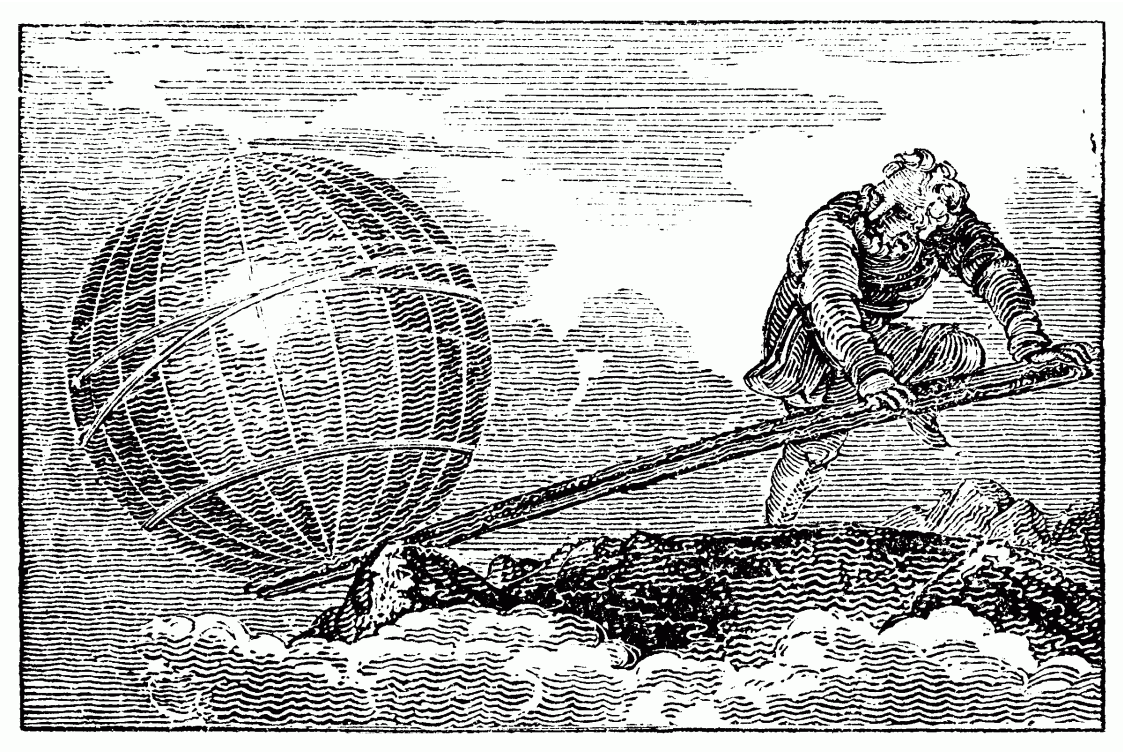
Science Olympiad
Machines C
Las Vegas Invitational

December 19, 2020



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:
Jessica Shah, *jessica.shah@duke.edu*
Robert Lee, *robertyl@ucla.edu*

Feedback? **Test Code**: *2021SOLVI-MachinesC-Shear*

Section A: Multiple Choice

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

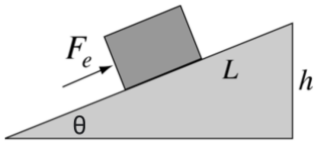
1. What is the most common lever in the human body?
   A. First Class
   B. Second Class
   C. Third Class
   D. Low Class
   E. Middle Class
   F. High Class

2. When you are biting into Korean BBQ Short Ribs, your teeth act like this simple machine:
   A. Screw
   B. Lever
   C. Wheel and Axle
   D. Wedge
   E. Pulley
   F. Inclined Plane

3. Which of the following conditions would create the most efficient forearm?

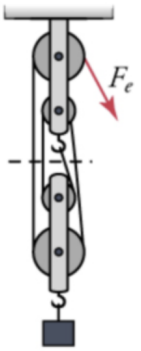
   A. Distance between the muscle insertion site and the joint is **greater than** the distance between the load and the joint
   B. Distance between the muscle insertion site and the joint is **less than** the distance between the load and the joint
   C. Distance between the muscle insertion site and the joint is the **same as** the distance between the load and the joint
   D. Distances do not affect efficiency

4. What is the required force to push an object of mass M up an incline? (Select all that apply)



   A. $Mg\sin\theta$
   B. $Mg\cos\theta$
   C. $MghL$
   D. Mgh/L
   E. $Mgh\sin\theta$
   F. $Mgh\cos\theta/L$

5. What is the mechanical advantage of this pulley?



   A. 1
   B. 2
   C. 3
   D. 4
   E. 5
   F. 6

6. A force of 5 N acts on the effort arm of a lever moving 1 m, which lifts a 20 N box of N95 face masks resting on the resistance arm a distance of 0.1 m. What is the efficiency of the machine?

   A. 30 %
   B. 40 %
   C. 50 %
   D. 60 %
   E. 70 %
   F. 80 %

7. A 75 N box of hand sanitizers rests on a plane inclined at 10° to the horizontal. The coefficient of static friction is 0.2 between the box and the plane, and the coefficient of kinetic friction is 0.15. What is the force F parallel to the plane required to move the sled up at constant velocity?

   A. 24.1 N
   B. 27.8 N
   C. 75.8 N
   D. 76.5 N

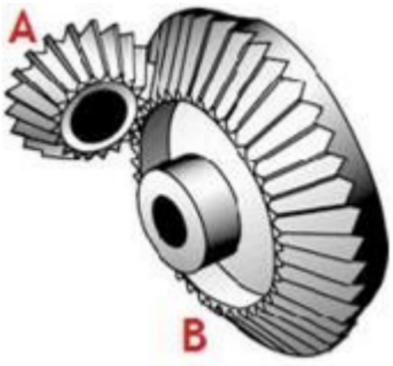
8. Snowy the polar bear exerts a 300 N force on a lever to raise a 1500 N fish-shaped rock a distance of 15 cm. If the lever has an efficiency of 78.2 %, how far did Snowy have to push their end of the lever?

   A. 6.4 cm
   B. 10 cm
   C. 19 cm
   D. 75 cm
   E. 96 cm

9. Snowy the Polar Bear is locked out from his home, so he uses the curved-end of a crowbar to pry open the door. What class lever is the crowbar?

   A. First Class
   B. Second Class
   C. Third Class
   D. Low Class
   E. Middle Class
   F. High Class

10. If gear A is rotating counterclockwise, what direction is gear B rotating?

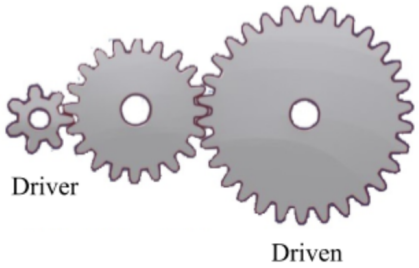


   A. Clockwise
   B. Counterclockwise
   C. It doesn't move

11. What do you need to determine how fast a gear is turning in relation to another? (Select all that apply)
    A. Direction the gears are turning
    B. Diameter of the gears
    C. Number of teeth
    D. Distance between the centers of the gears

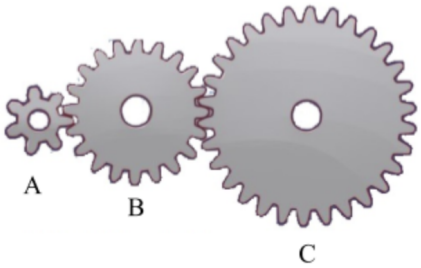
12. Assume more than two gears are together. The larger gear will rotate _____ than the smaller gear.
    A. Faster
    B. Slower
    C. Same speed

13. What is the purpose of the center gear? (Select all that apply)



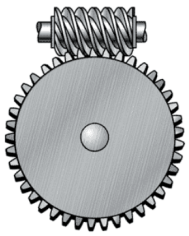
    A. Increase the torque of the driven gear
    B. Increase the RPM of the driven gear
    C. Allow the driver and the driven gear to rotate in the same direction
    D. Allow the driver and the driven gear to rotate in the opposite direction

14. Gear A has 7 teeth, Gear B has 20 teeth, and Gear C has 30 teeth. What is the overall gear ratio of this gear train?



    A. 1.50
    B. 2.90
    C. 4.30
    D. 4.35
    E. 6.45

15. What type of gear system is this?



    A. Bevel gear
    B. Helical gear
    C. Miter gear
    D. Rack and pinion
    E. Spur gear
    F. Worm gear

16. Snowy the Polar Bear is lifting a 350 N crate of Snowy the Polar Bear™ stuffed animals by pulling with a force of 40 N on the rope of a single pulley. What is the actual mechanical advantage of the system?
    A. 1.2
    B. 8.5
    C. 8.75
    D. 14

17. Snowy the Polar Bear is using a jackscrew with a handle 75.0 cm long to lift a Snowy statue setting on the jack. The Snowy status is raised 3.0 cm with every full turn of the handle. What is the ideal mechanical advantage of the jack?

    A. 39.3

    B. 78.5

    C. 157

    D. 199

18. A 25 % efficient jack has a handle of 30 cm and a pitch of 0.6 cm. What is the actual mechanical advantage of the jack?

    A. 11.5

    B. 39.3

    C. 72.0

    D. 78.5

19. Snowy the Polar Bear is 500 N and decides to sit on a seesaw 1.5 m from the pivot point. He invites a 355 N polar bear to join him. Where should the 355 N polar bear sit so that they are balanced on a horizontal position?

    A. 1.07 m

    B. 1.11 m

    C. 2.07 m

    D. 2.11 m

20. Given a wheel radius R and axle radius r, what is the IMA of a wheel-axle system?

    A. $\frac{R-r}{r}$

    B. $\frac{R}{r}$

    C. $\frac{R-r}{R}$

    D. $\frac{r}{R}$

    E. $\frac{R+r}{r}$

    F. $\frac{R+r}{R}$

21. A wedge has a side length L and thickness h. What is the IMA of a wedge?

    A. $\frac{L}{2h}$

    B. $\frac{2L}{h}$

    C. $\frac{L}{h}$

    D. $\frac{h}{L}$

    E. Lh

    F. $L + h$

22. Snowy the Polar Bear is trying to chop a tree with an axe, but his axe is too dull. What should he do to fix his axe?

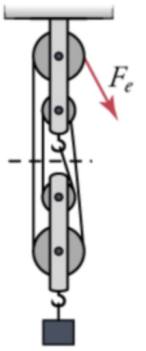
    A. Increase wedge length and increase wedge separation

    B. Increase wedge length and decrease wedge separation

    C. Decrease wedge length and increase wedge separation

    D. Decrease wedge length and decrease wedge separation

23. Snowy the Polar Bear is trying to lift a 100 N box of golden fish using the pictured pulley system, how much effort must he exert to lift the load?



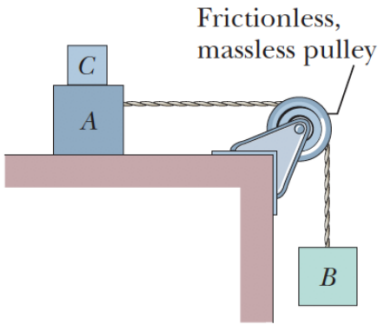
    A. 25 N

    B. 33 N

    C. 50 N

    D. 100 N

The following two questions refer to the image shown below.



24. Blocks A and B have weights of 50 N and 25 N. What is the minimum weight of C to keep A from sliding if the coefficient of static friction between A and the table is 0.2 N?

    A. 25 N

    B. 50 N

    C. 75 N

    D. 100 N

25. Blocks A and B have weights of 50 N and 25 N. Block C is suddenly lifted off of block A. What is the acceleration of A if the coefficient of kinetic friction between A and the table is 0.15?

    A. $2.29\,\mathrm{m\,s^{-2}}$

    B. $2.55\,\mathrm{m\,s^{-2}}$

    C. $5.10\,\mathrm{m\,s^{-2}}$

    D. $6.04\,\mathrm{m\,s^{-2}}$

26. Snowy the Polar Bear is racing his friend Ice Bear and has half the kinetic energy of Ice Bear, who has half the mass of Snowy. Snowy speeds up by $1.5\,\mathrm{m\,s^{-1}}$ and then has the same kinetic energy as Ice Bear. What was the original speed of Snowy the Polar Bear?

    A. $0.6\,\mathrm{m\,s^{-1}}$

    B. $0.8\,\mathrm{m\,s^{-1}}$

    C. $3.6\,\mathrm{m\,s^{-1}}$

    D. $3.8\,\mathrm{m\,s^{-1}}$

27. A double start screw has a pitch of 3 mm and advanced to 9 cm. How many revolutions did it make?

    A. 10

    B. 15

    C. 18

    D. 30

28. A triple start screw goes through 12 rotations to advance 18 cm. What is the pitch of the screw?

    A. 1.5 mm

    B. 5.0 mm

    C. 6.0 mm

    D. 15 mm

    E. 16 mm

29. Three simple machines with mechanical advantages A, B, and C are in series with each other to form a compound machine. What is the mechanical advantage of the compound machine?

    A. $A + B + C$

    B. ABC

    C. $\frac{A+B+C}{3}$

    D. $\sqrt{A^2 + B^2 + C^2}$

    E. None of the above

30. Snowy the Polar Bear is pushing a fish-shaped 100 N sled up a frictionless icy hill of height 20 m. If Snowy uses 75 N to push the sled up the slope, what is the distance between the base of the hill and the top of the hill?

    A. 15 m

    B. 17 m

    C. 25 m

    D. 27 m

    E. 35 m

    F. 37 m

Section B: Free Response

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

1. (14 points) April is pushing a 3000 kg box up a rough inclined plane with constant velocity. She pushes with a force of 1100 N along the inclined plane over 70 m. This process takes 7 minutes and results in a vertical displacement of 1.19 m.

   (a) (2 points) How much work is done by April, in J?

   (b) (3 points) Is the inclined plane self-locking? Explain why.

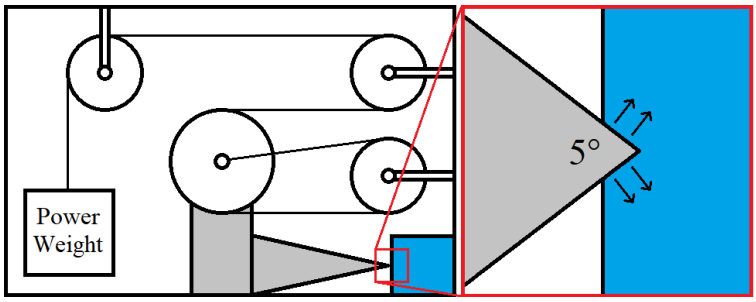
   (c) (3 points) What is the coefficient of kinetic friction between the box and the plane? (Show 5 or more significant figures)

   Once April reaches the top of the inclined plane, she finds another inclined plane on the other end, sloping at a 25° decline. This inclined plane is made from ice and has a low coefficient of kinetic friction ($\mu_k = 0.05$). She conjures a sled from the ether and slides down the icy ramp with a running start of $0.05\,\mathrm{m\,s^{-1}}$.

   (d) (3 points) How much time does it take her to slide down 100 m of ramp, in s?

   (e) (3 points) What is her velocity at the moment she travels 100 m, in $\mathrm{m\,s^{-1}}$?

2. (29 points) Your friend devised a groundbreaking drill design that they are hoping to patent. The design, shown below, consists of a system of four pulleys and a novel drill bit shaped like a wedge. The drill bit is a triangular prism, with a 1 cm thickness (the dimension out of the page), kept aligned by a rail on the ground. The system is powered by a lifted and lowered weight. The blue square represents a piece of ore.



(a) (2 points) Find the IMA of the drill design.

(b) (12 points) Your friend came with two ways to use the device. Method one: move the drill bit so that it is just touching the ore, release the 50 kg Power Weight™, and let the drill slowly push into the ore.

i. (6 points) Let $P(d)$ be the pressure exerted by the wedge (the arrows in the right diagram) as a function of depth (initially at 0). $P(d)$ is in pascals and d is in meters. $P(d)$ can be represented in the form ad^b, find a and b.

ii. (3 points) The compressive strength of the ore is 15 MPa. How deep can the device drill, in m?

iii. (3 points) In practice, the device is only able to drill to 75 % of the predicted depth. Give a possible reason why that is the case and provide a reasonable remedy for this inefficiency.

(c) (15 points) Due to budget cuts and high tariffs, your friend can only purchase a 20 kg Power Weight™. They decide to use the other method to operate the device. Method two: pull the 100 kg drill bit back until the weight is lifted 1.5 m off the ground, release the drill bit and let the weight fall, and, right after the weight hits the ground, the drill bit hits the ore and comes to rest.

i. (3 points) What is the speed of the drill bit once the Power Weight™ hits the ground, in $\mathrm{m\,s^{-1}}$?

ii. (3 points) How much energy is lost through this process, in J?

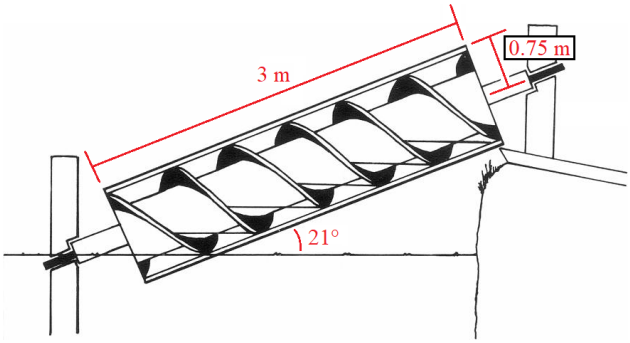
iii. (3 points) Let's assume the drill bit comes to rest after 0.1 s. Find the average force exerted by the ore onto the drill bit, in N?

iv. (6 points) Calculate how deep the device drills until it comes to rest, in m. *(This is a challenge problem, make sure to explain your answer in depth.)*

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 a **class 1 lever** connected to a **class 2 lever**.
   (a) (8 points) Draw a labeled device diagram with dimensions.
   (b) (4 points) Make an itemized list of the materials used in the design and the tools needed.
   (c) (4 points) Describe the construction process of the design.
   (d) (6 points) Consider two potential sources of error and explain how you will minimize their effects.
   (e) (8 points) Finally, thoroughly explain the testing process for two mass ratios: 10:1 and 3:1. In your explanation, include a diagram of the mass locations and run through the appropriate calculations.

4. (17 points) Shown below is a schematic of an Archimedes screw used for pumping up water. The frictionless, double-started screw makes 3 full rotations and is housed in a metal cylinder with a length of 3 m, a radius of 0.75 m, and a negligible thickness. The screw is placed at 21° with respect to the horizontal.

   The machine will be powered by a 300 W motor attached at the top of the screw. The motor's torque consists of a force applied at the radius of the screw.



   (a) (2 points) What is the IMA of the machine?
   (b) (4 points) Each of the six troughs contain 20 L of water. What must the torque of the motor be to lift the water at a constant velocity, in N m? *(Hint: the density of water is* $1\,\mathrm{g\,cm^{-3}}$*)*
   (c) (4 points) Compute the average flow rate of water up the screw, in $\mathrm{L\,s^{-1}}$.
   (d) (7 points) After shopping around online, you find it is too expensive to buy a 300 W motor with that torque. You decide to settle with a cheaper, 200 W motor that can output a torque of 45 N m.
      i. (2 points) Looking at the value we found in (b), we can see that the required torque exceeds the motor's torque. We can design a transmission to gear down the motor. What is our target gearing ratio (x:1)? (Use 127 N m if you did not solve (b))
      ii. (5 points) The transmission will follow the layout shown below, with gears B/C axially connected and where gear A is the input (motor) and gear D is the output (screw). How many teeth (from 10 to 50) should each of the four gears have to most closely match the gearing ratio in (d.i)? *(Remember, teeth only come in whole numbers!)*