Filled Ball

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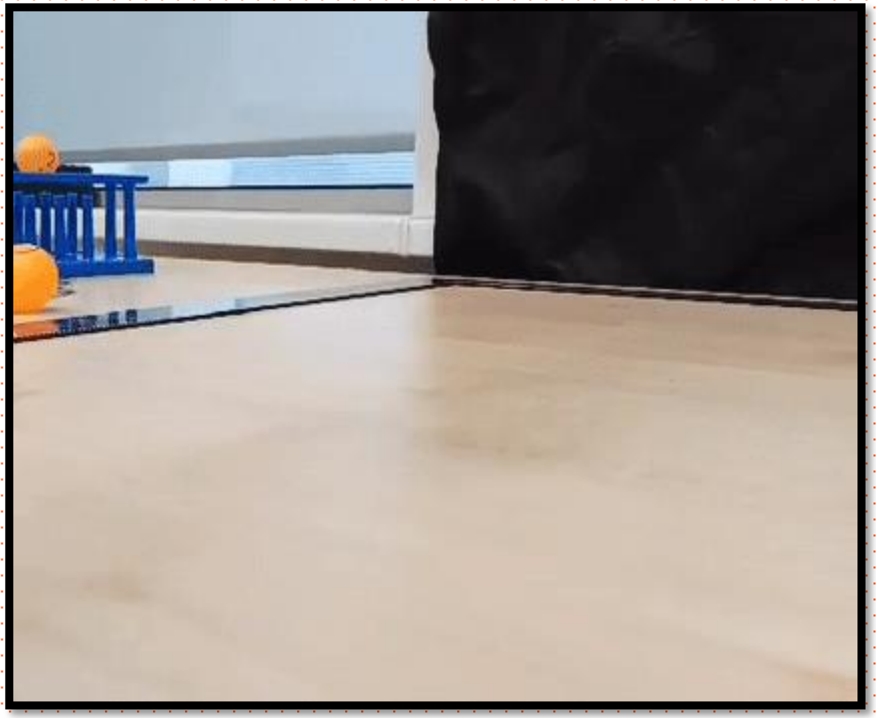
The problem

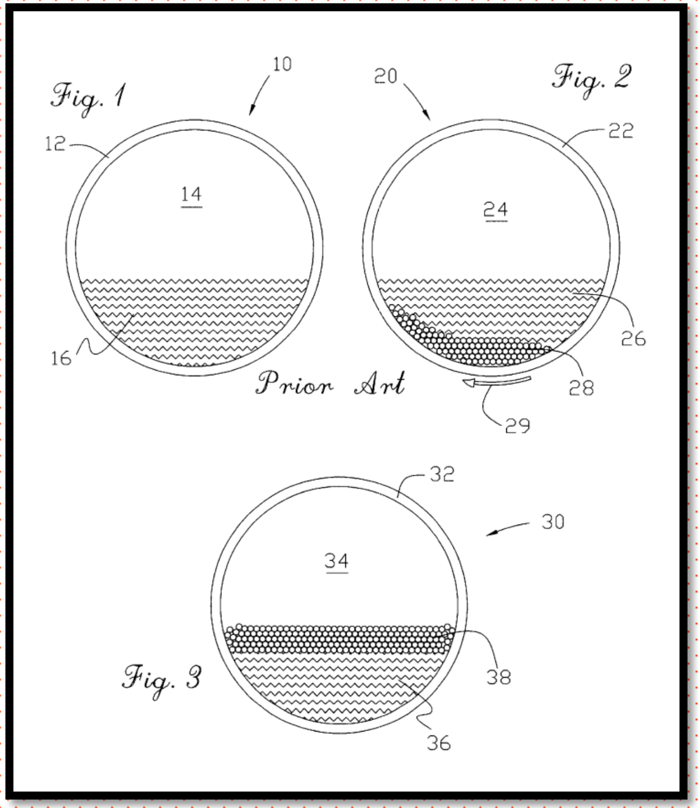
A ping-pong ball that has been partially filled with some fluid or sand will bounce much lower than a filled one. Explain this phenomenon. How does the height of the bounce depend on the relevant parameters?

First impressions

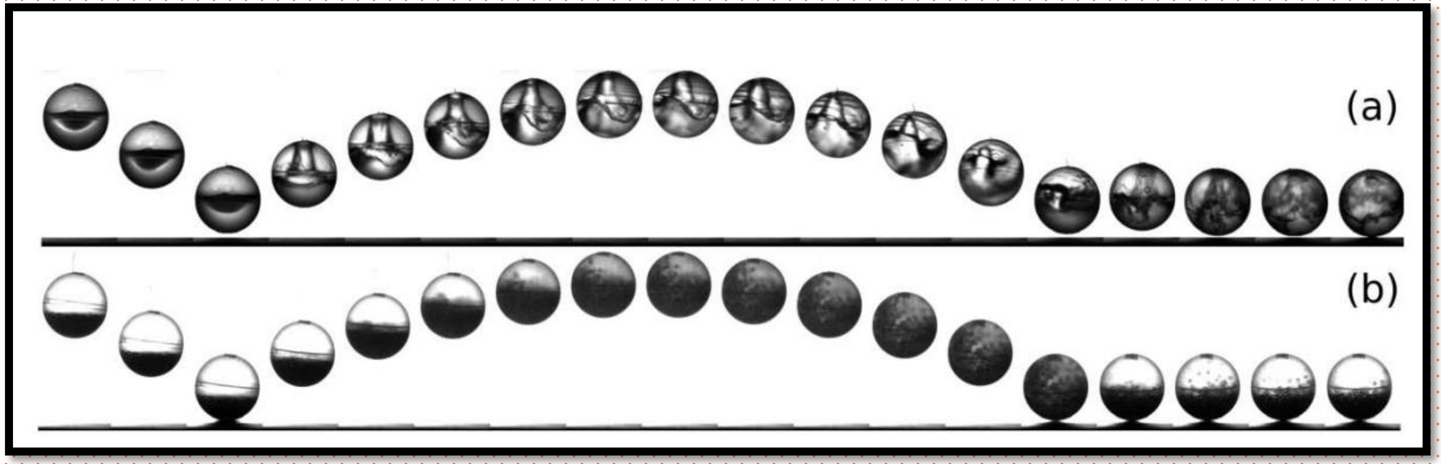
- Bounce height h <u>varies</u> for different same-height throws
- Bounce height is not proportional to initial height h_0 (damping)
- Lowest h (for given h_0) is for balls filled *around* halfway
- The ball starts to **roll**



Origin of the problem



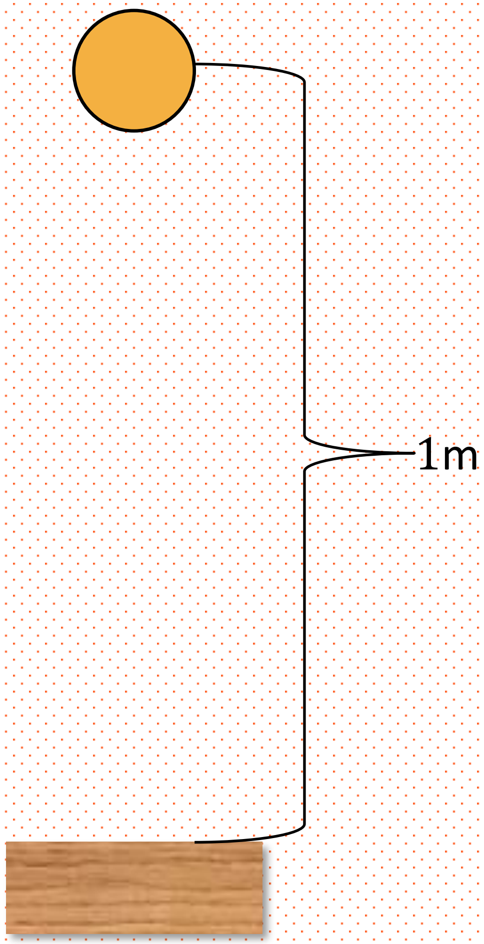
[1] – filled street hockey balls



[2] – bouncing sphere partially filled with water (a) and granular meterial (b)

[1]Street hockey ball, U.S. patent 6,645,098 (11 November 2003)
[2]T. W. Killian, R. A. Klaus, T. T. Truscott, Rebound and jet formation of a fluid-filled sphere

$m = (2.55 \pm 0.01)\text{g}$



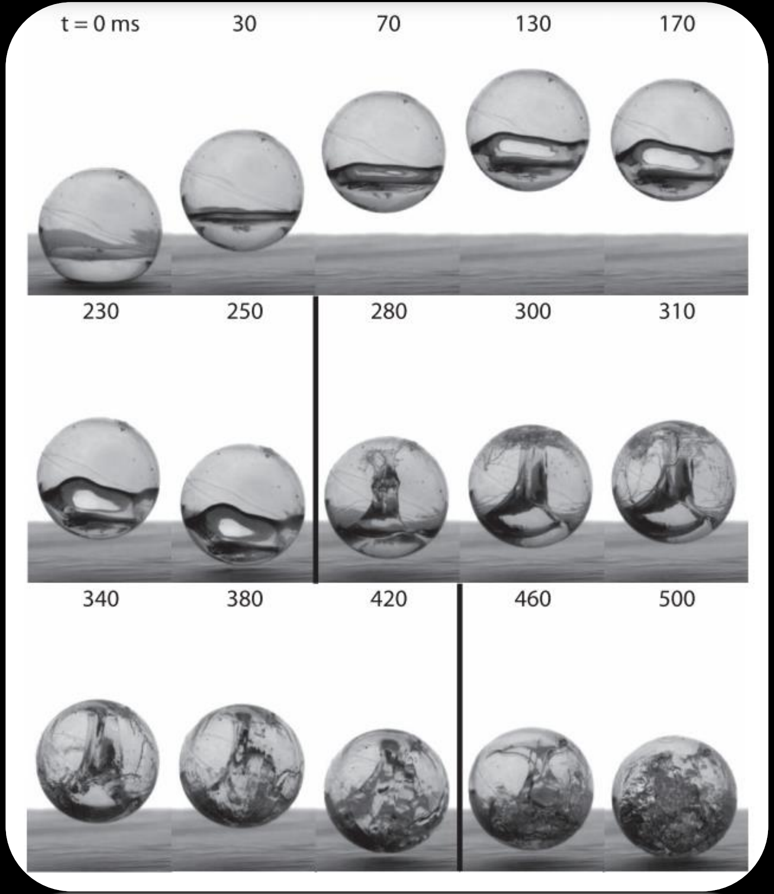
$$\left\langle \frac{h}{h_0} \right\rangle = 0.587 \pm 0.003$$

$$\alpha = \frac{E}{E_0} = \frac{h}{h_0}$$

60% of energy is conserved

Pacheco-Va´zquez , S. Dorbolo, *Rebound of a confined granular material: combination of a bouncing ball and a granular damper*

[3]



A ping-pong ball that has been partially filled will <u>bounce much lower</u> than a filled one.

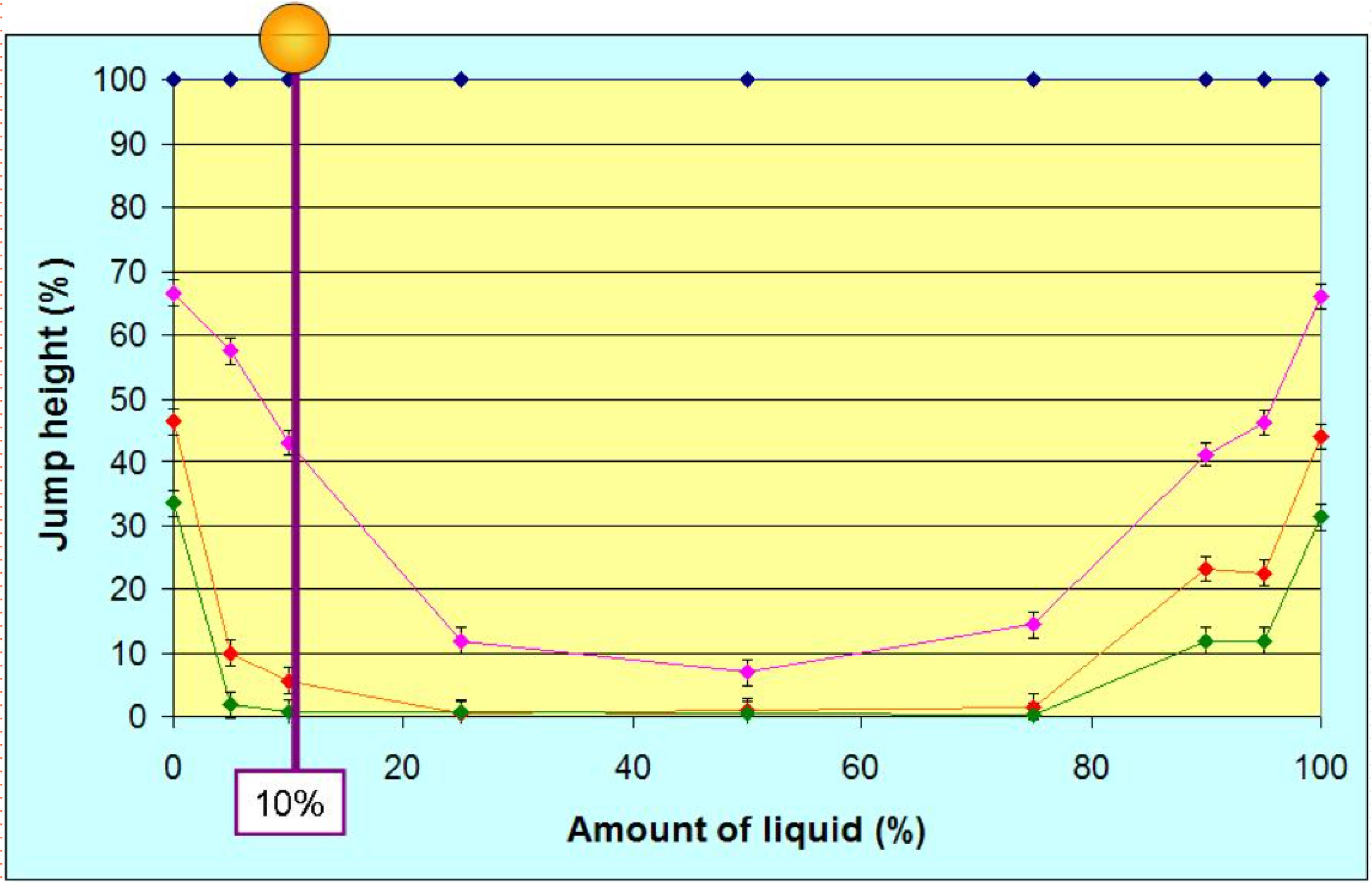
Previous investigations

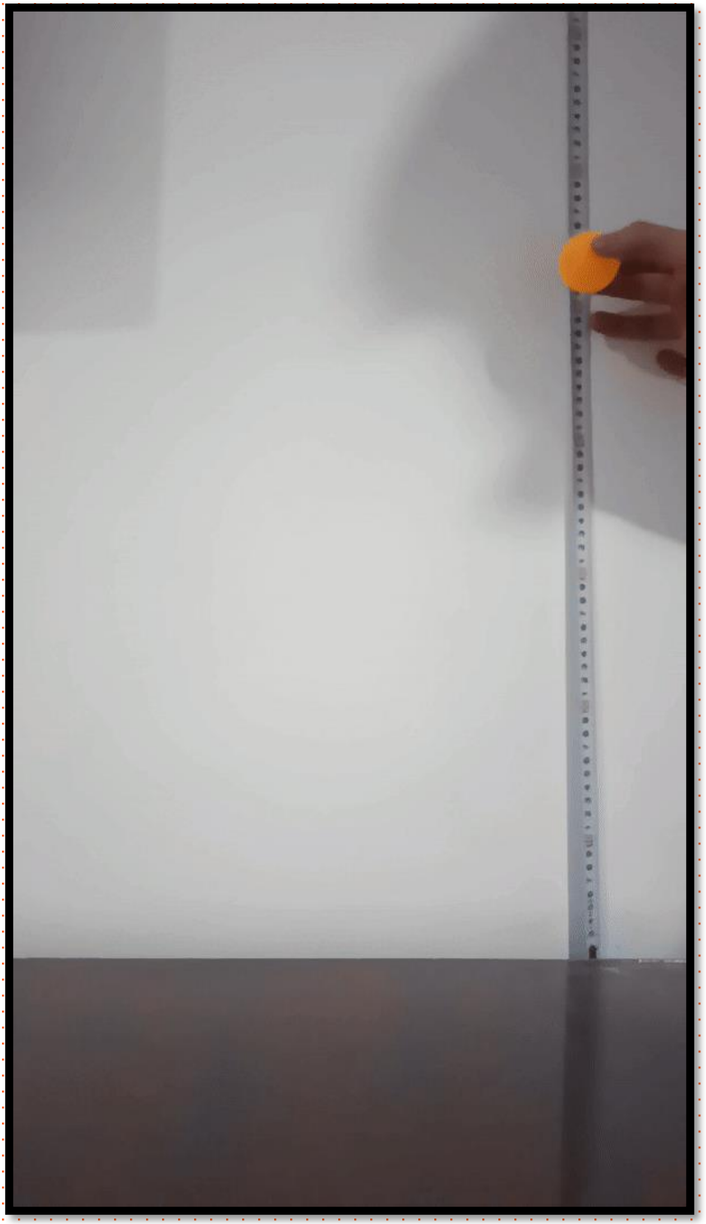
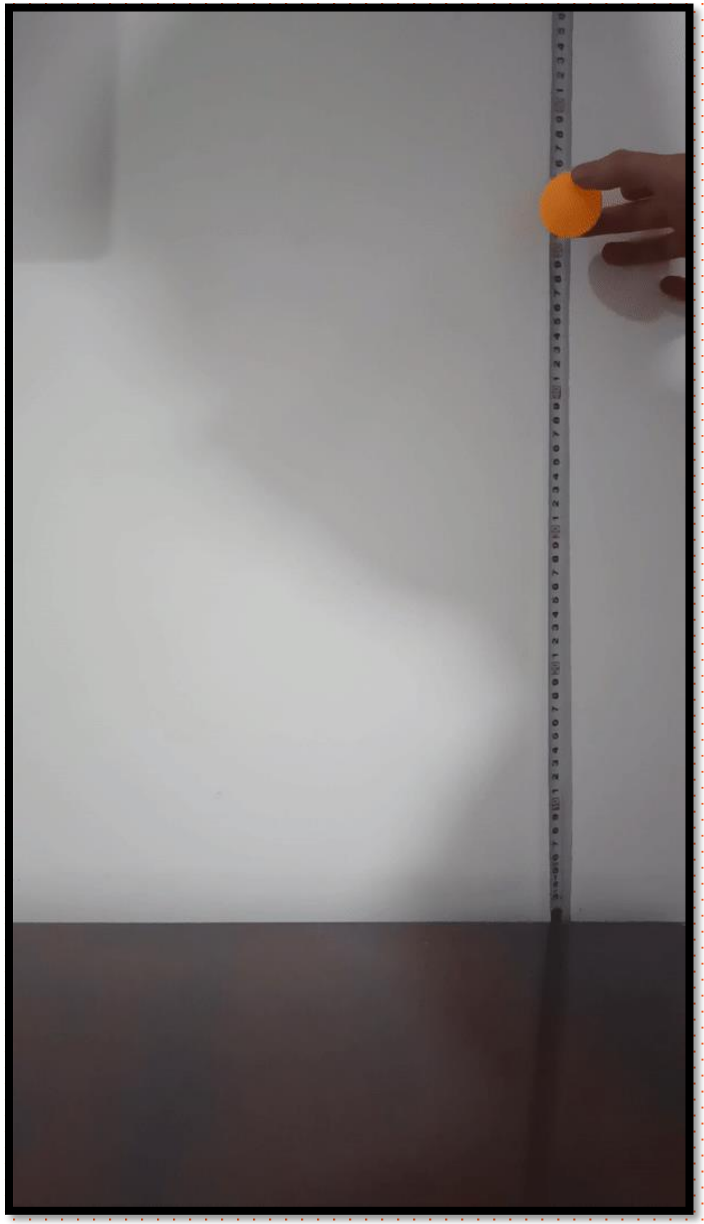
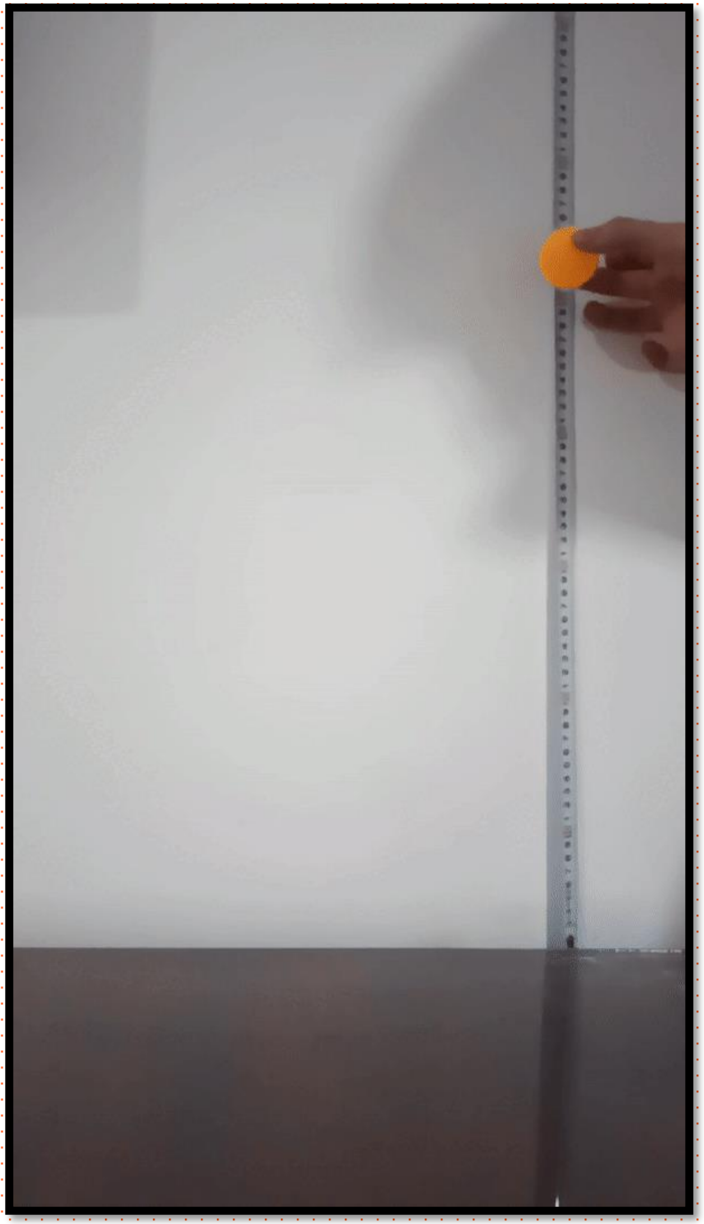
IYPT, 2014

Russian Team

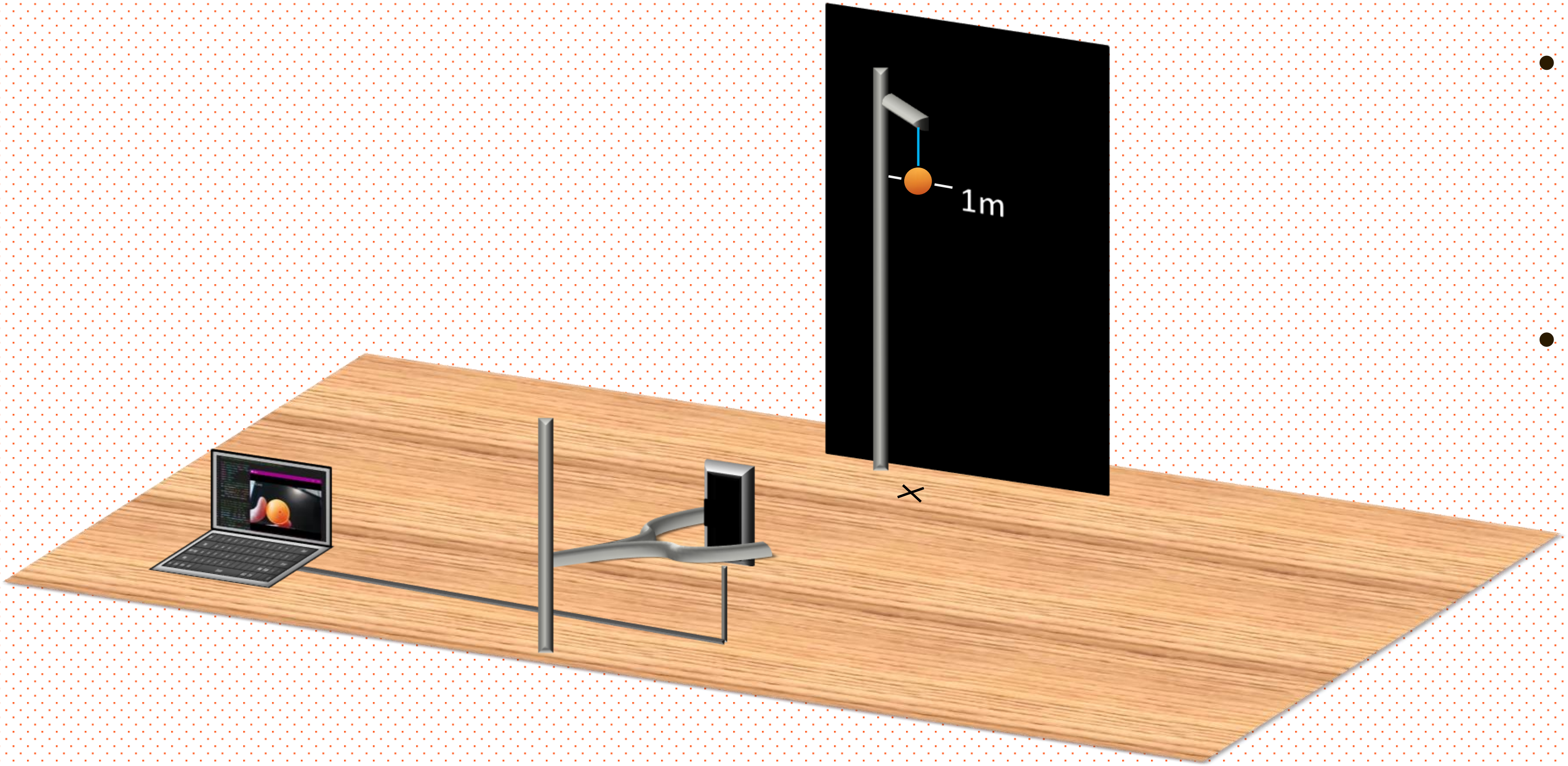
Ivan Chaika
Roman Doronin
Vitaliy Matiunin
Aleksandr Severinov
Vladislav Tumanov

Measurements done from 80cm



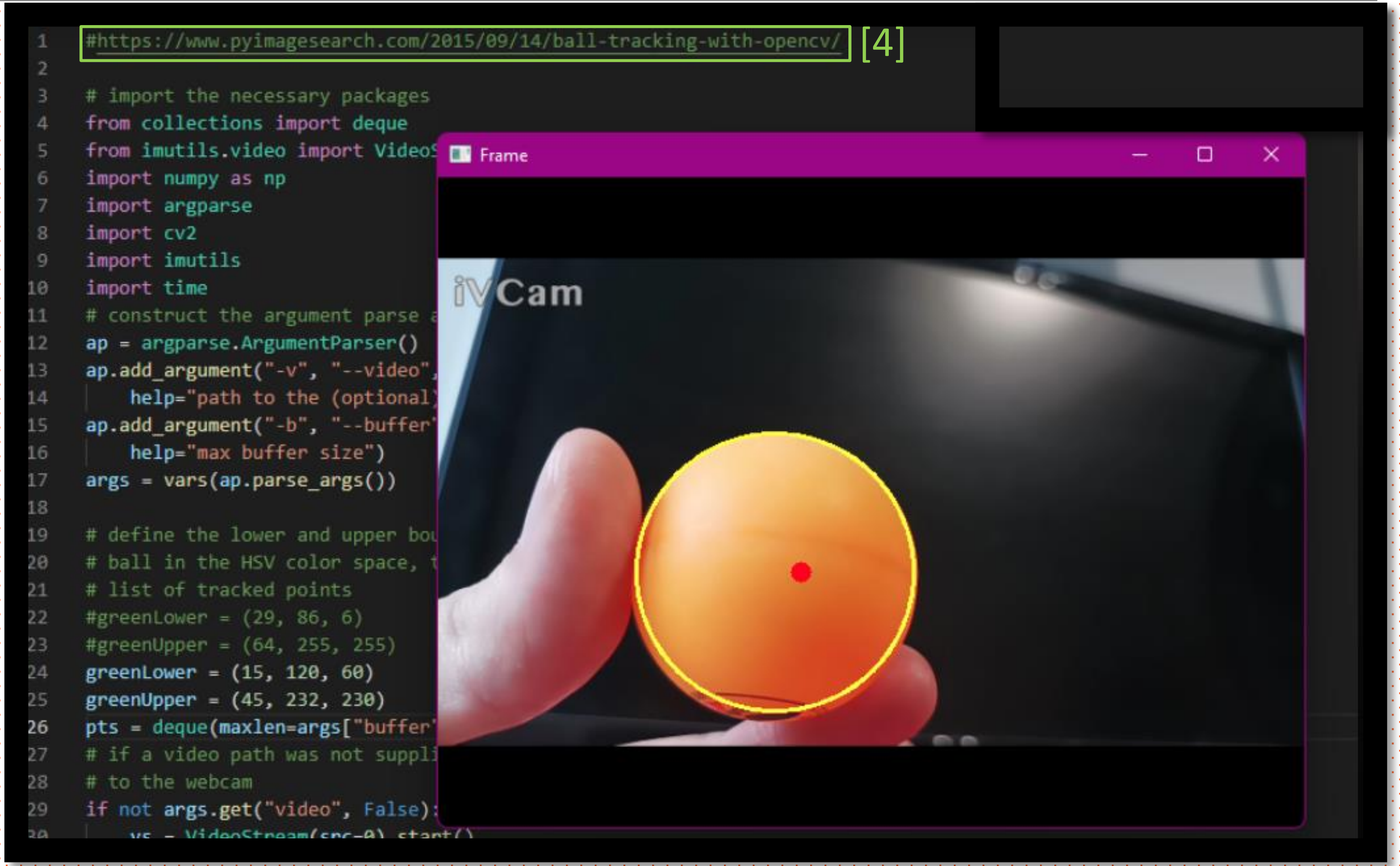
A ball with 2ml of water can bounce to either 20, 12 or 4 cm



- Motion of the ball established using a Python tracking code
- Ball is hanging on a string and is released by burning the string

Experimental setup

Tracker

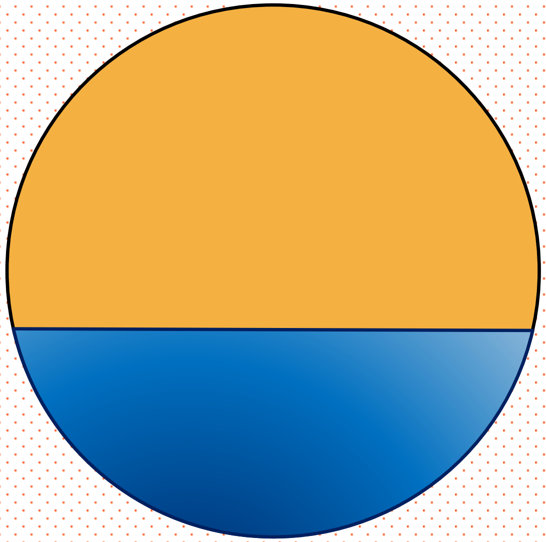

#https://www.pyimagesearch.com/2015/09/14/ball-tracking-with-opencv/
[4]
# import the necessary packages
from collections import deque
from imutils.video import Video
import numpy as np
import argparse
import cv2
import imutils
import time
# construct the argument parse
ap = argparse.ArgumentParser()
ap.add_argument("-v", "--video",
help="path to the (optional)
ap.add_argument("-b", "--buffer"
help="max buffer size")
args = vars(ap.parse_args())
# define the lower and upper bou
# ball in the HSV color space,
# list of tracked points
#greenLower = (29, 86, 6)
#greenUpper = (64, 255, 255)
greenLower = (15, 120, 60)
greenUpper = (45, 232, 230)
pts = deque(maxlen=args["buffer"
# if a video path was not suppli
# to the webcam
if not args.get("video", False):
Frame
iVCam

Ball mass around 2.5 g

Water

Maximum 30 grams

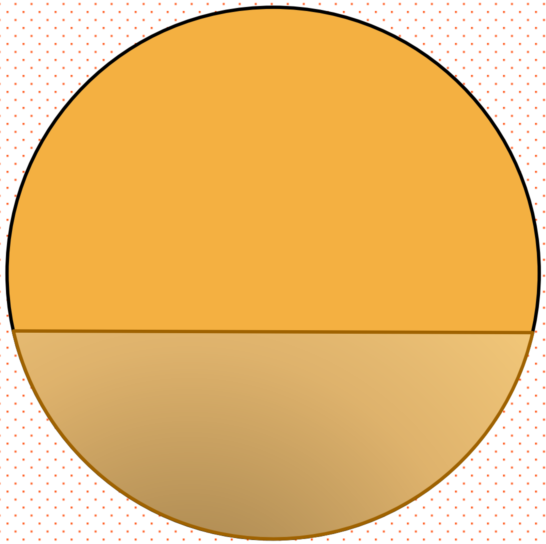
Measurements every 3 grams

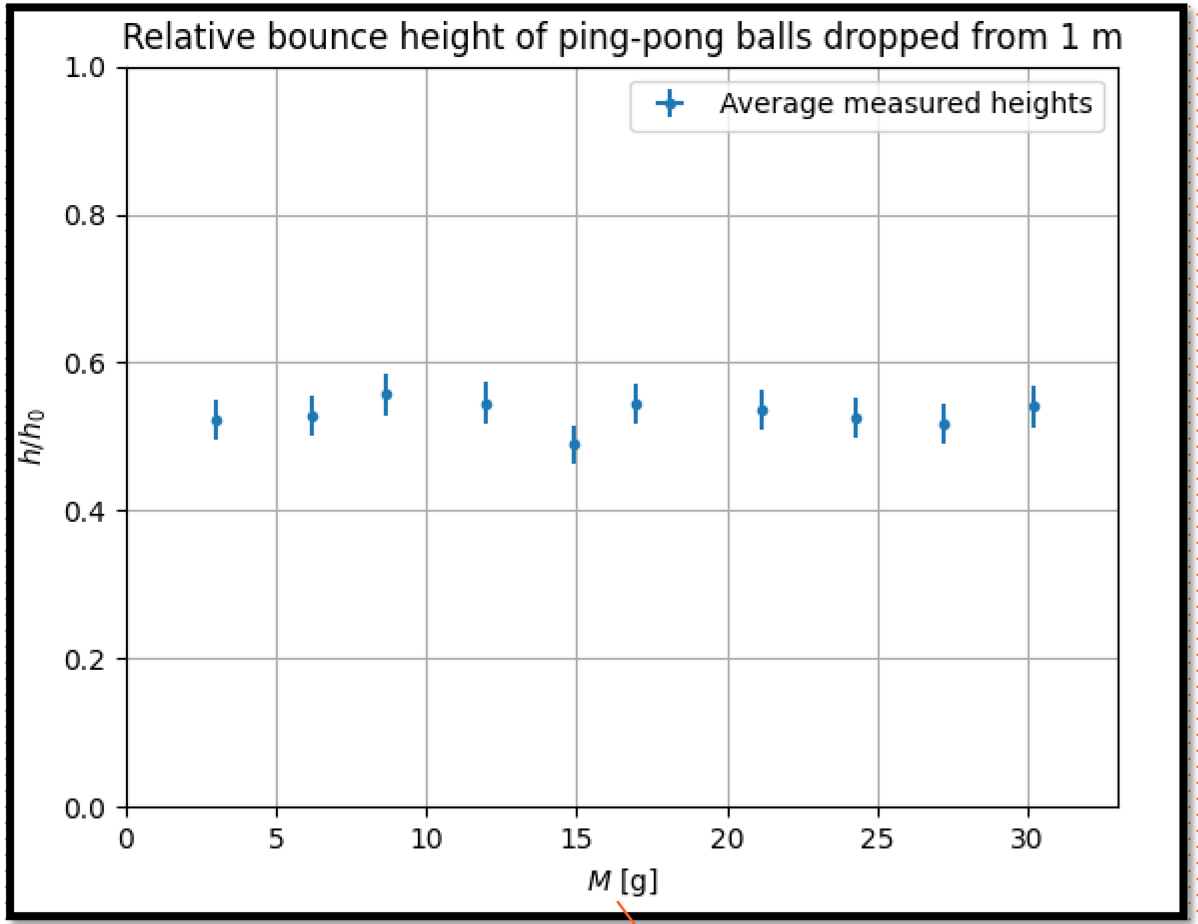


Sand

Maximum 52 grams

Measurements every 6 grams





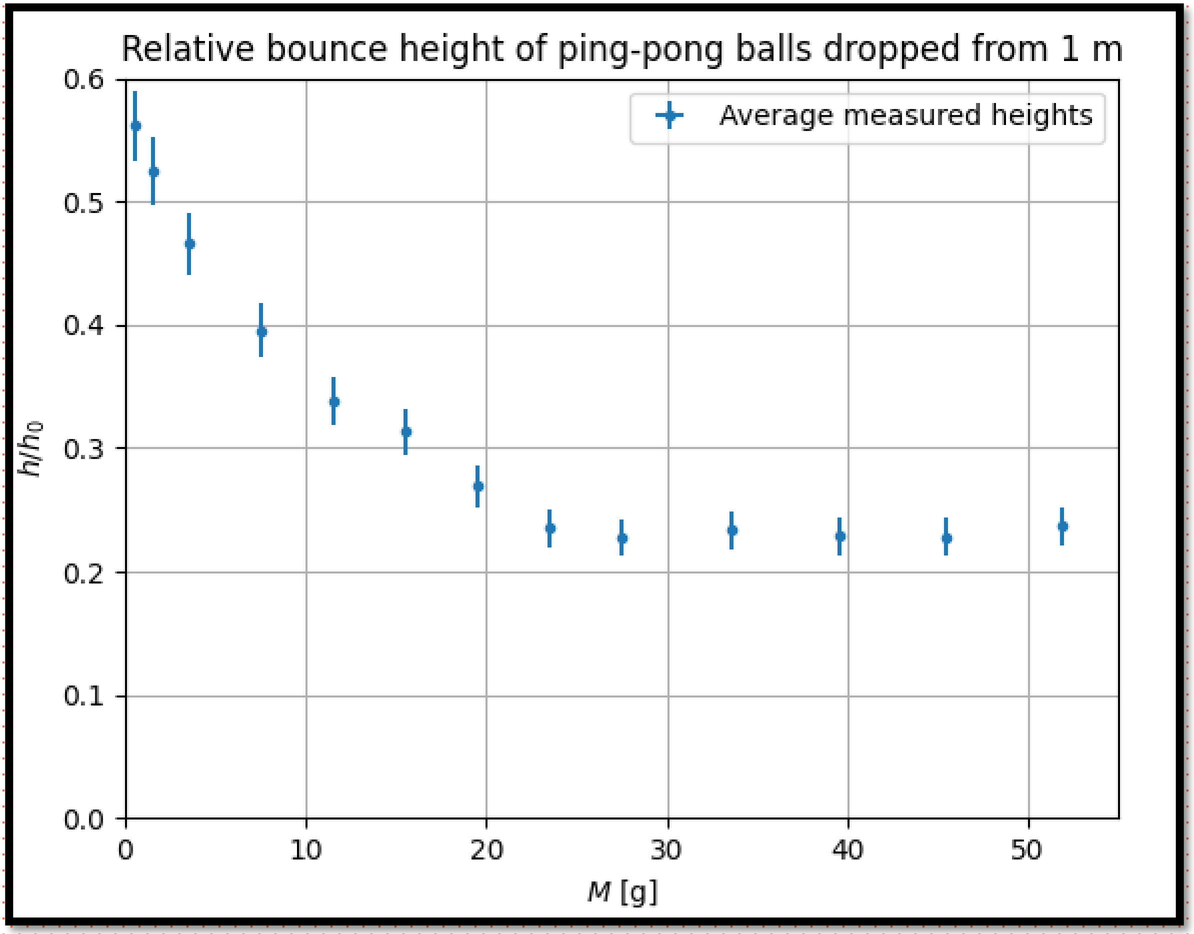
Filling mass

Results for water

Each data point is an average of three measurements.

Example

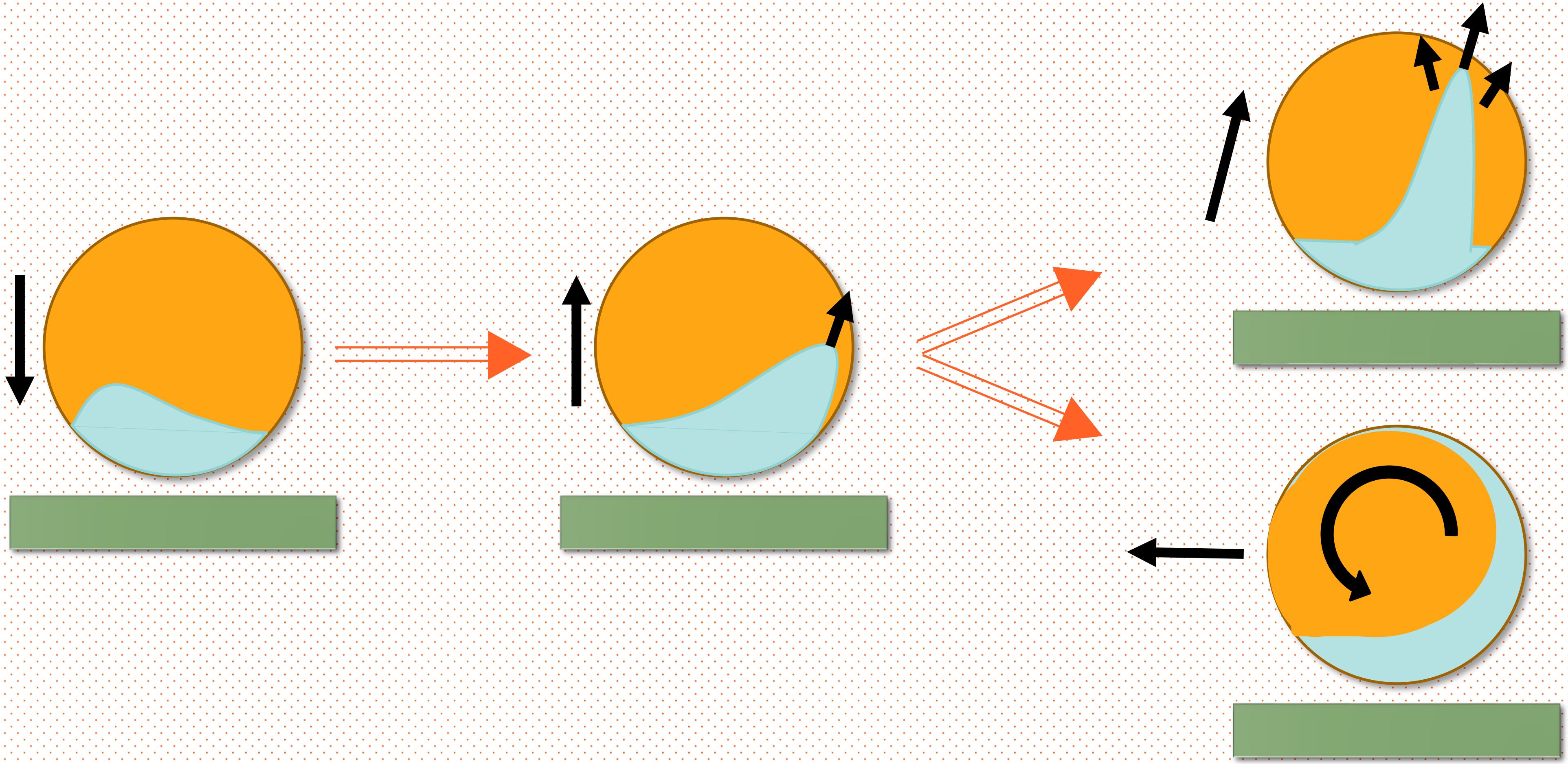
Notice how the ball doesn’t rebound the second time
Ball rebounds from 50 cm to 31 cm -> 0.6
15 ml water ball used

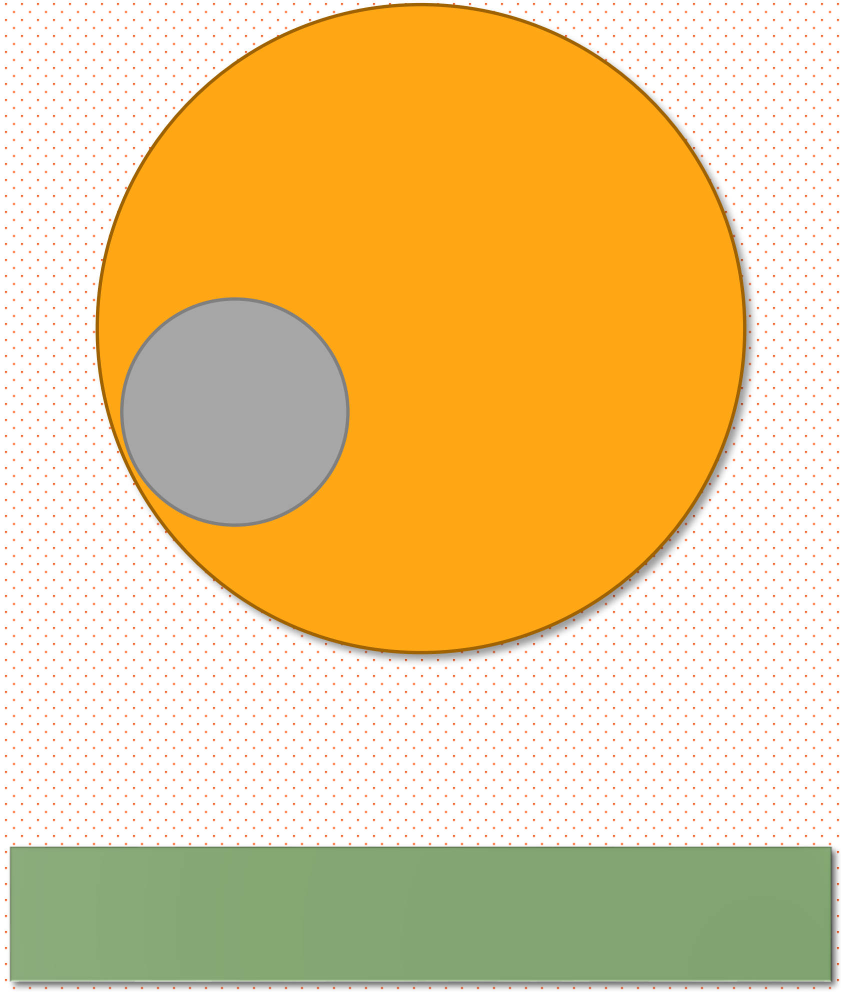


Results for sand

Each data point is an average of three measurements.

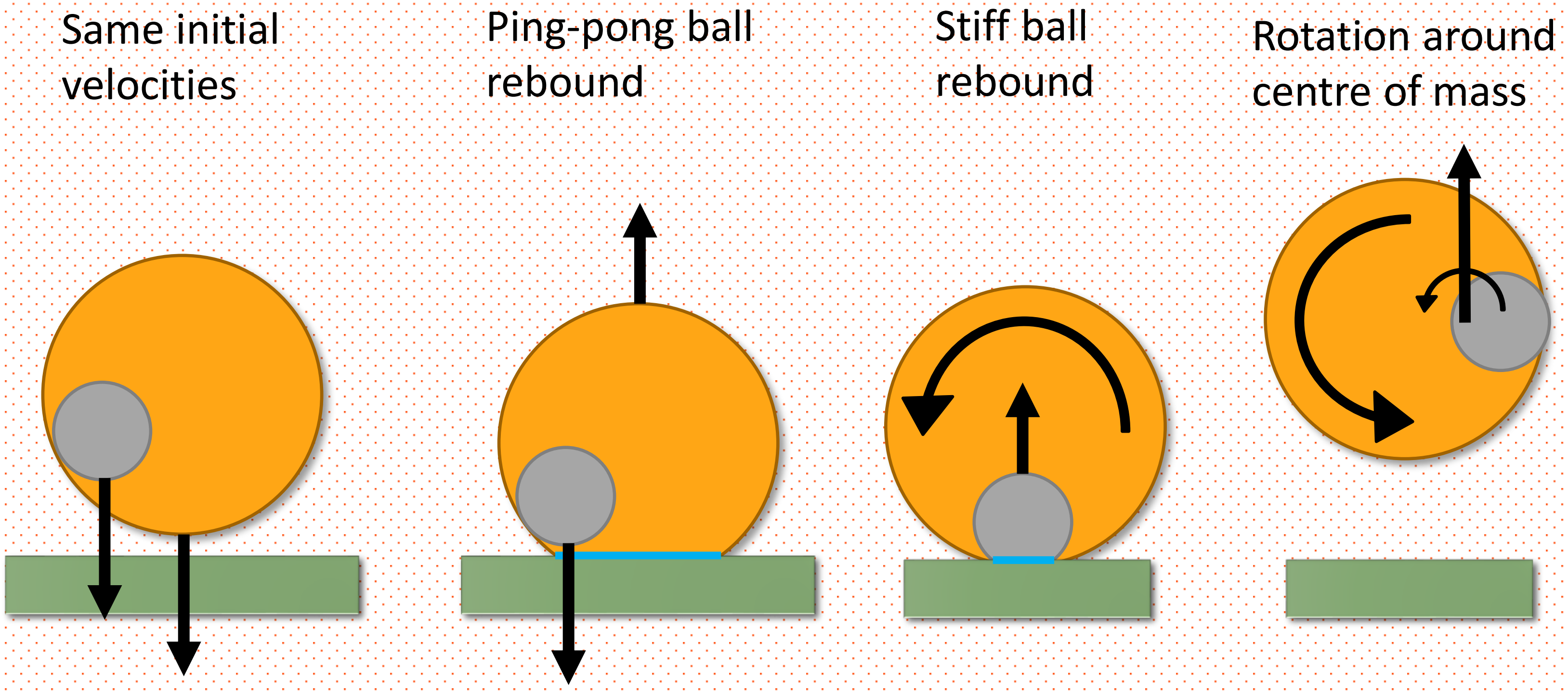
Energy losses



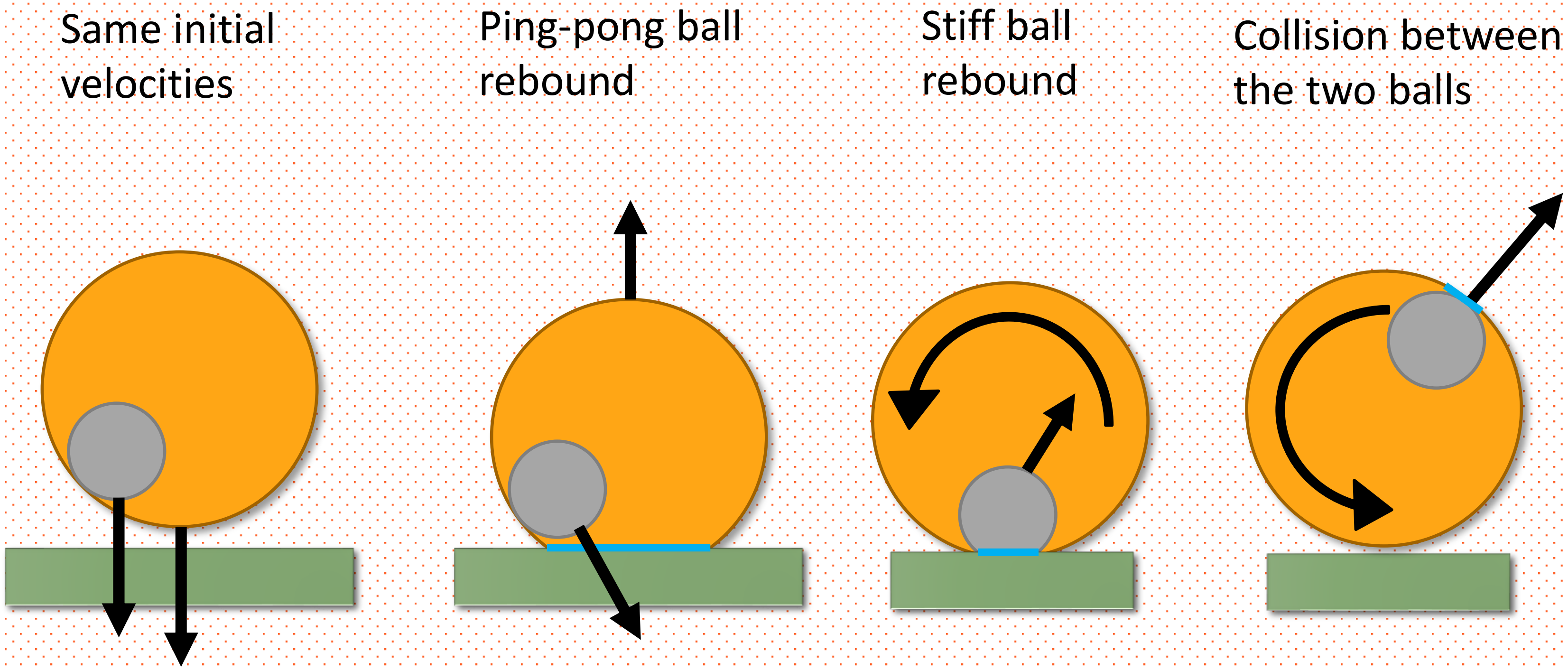


Inner ball analogy

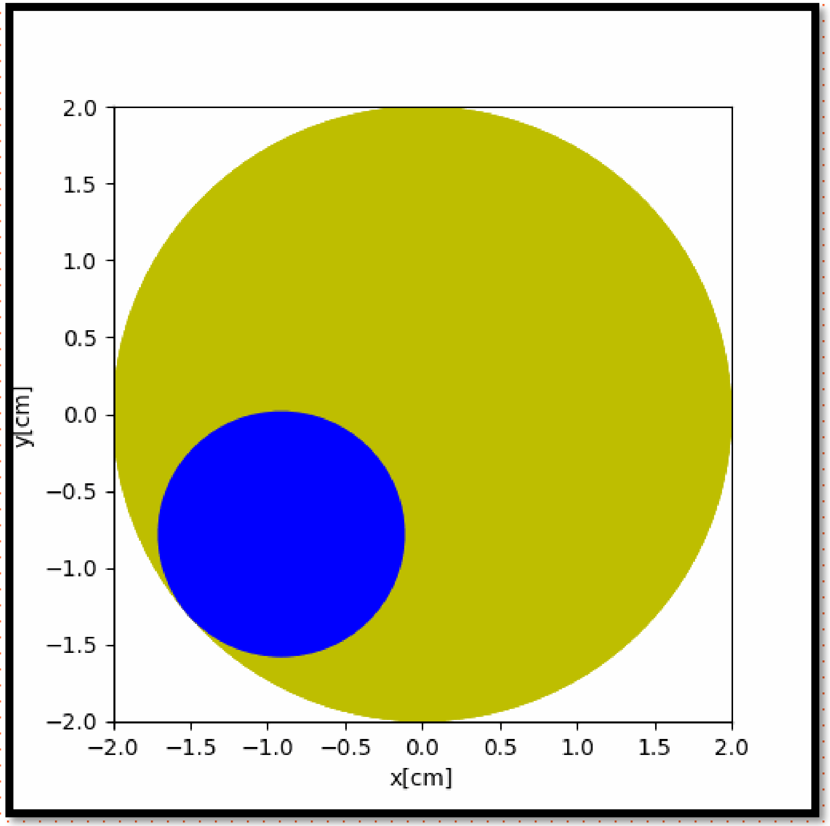
Stiff ball inside the sphere – rotation

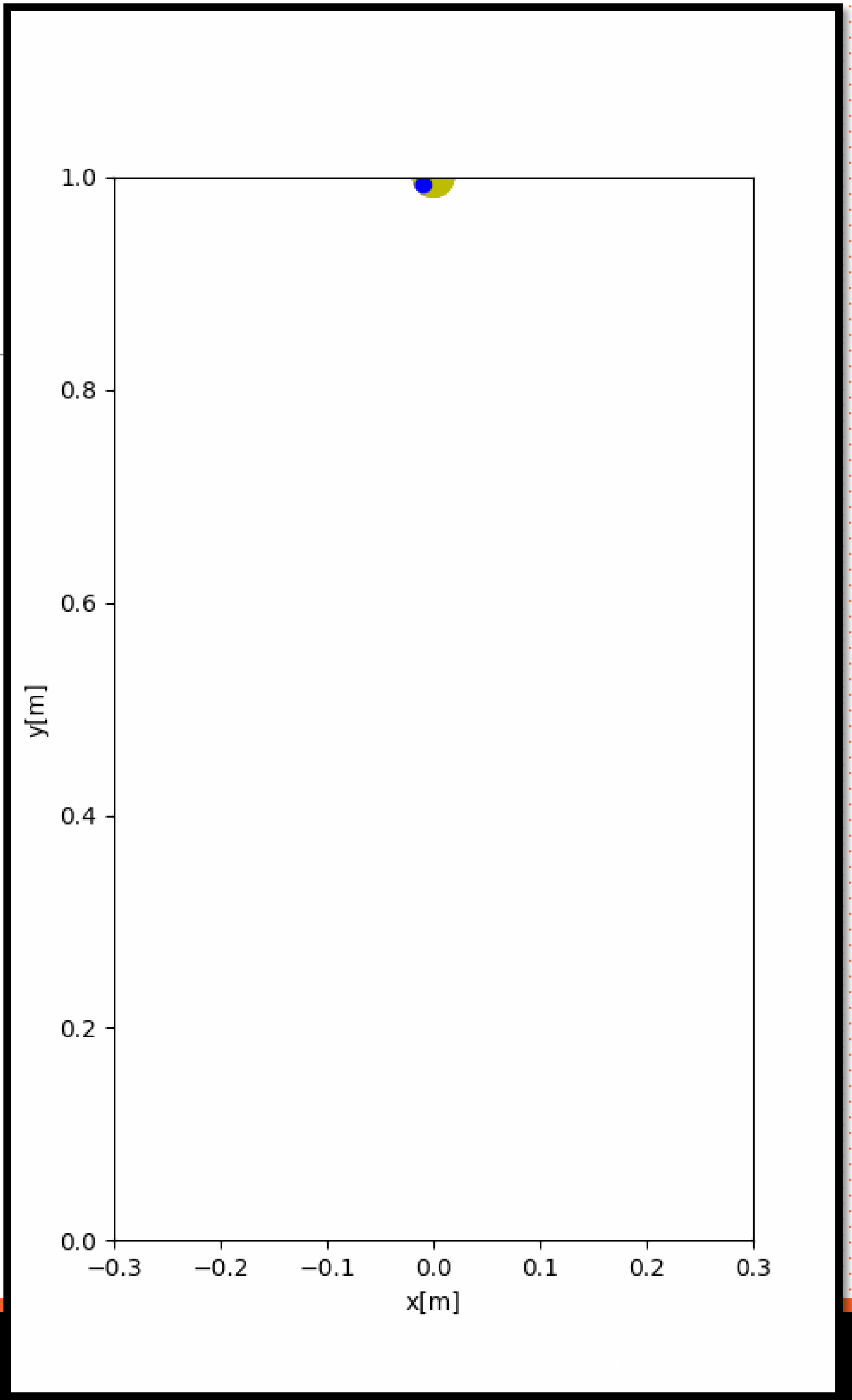


Stiff ball inside the sphere – ’jets’

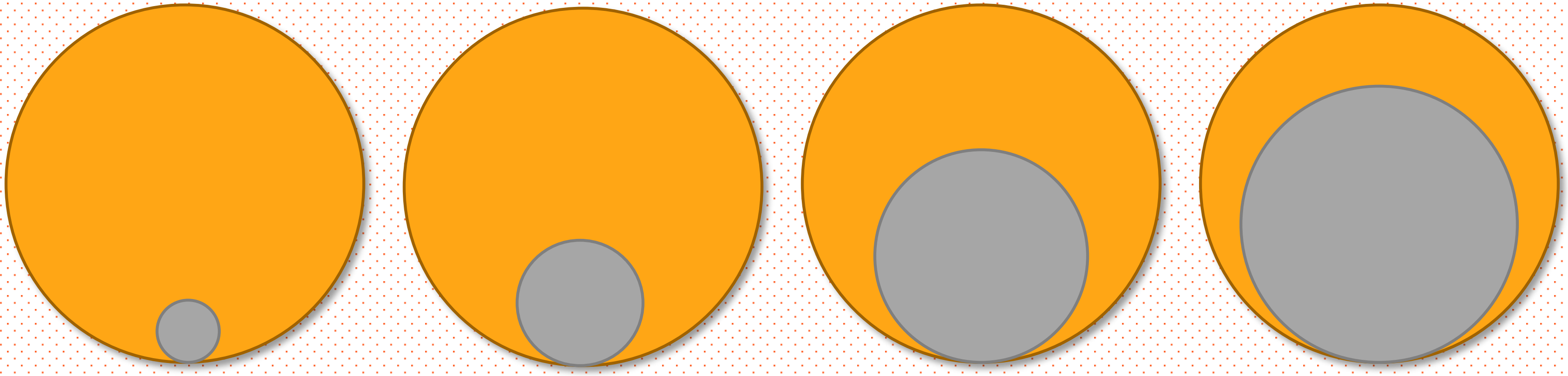


Numerical simulation

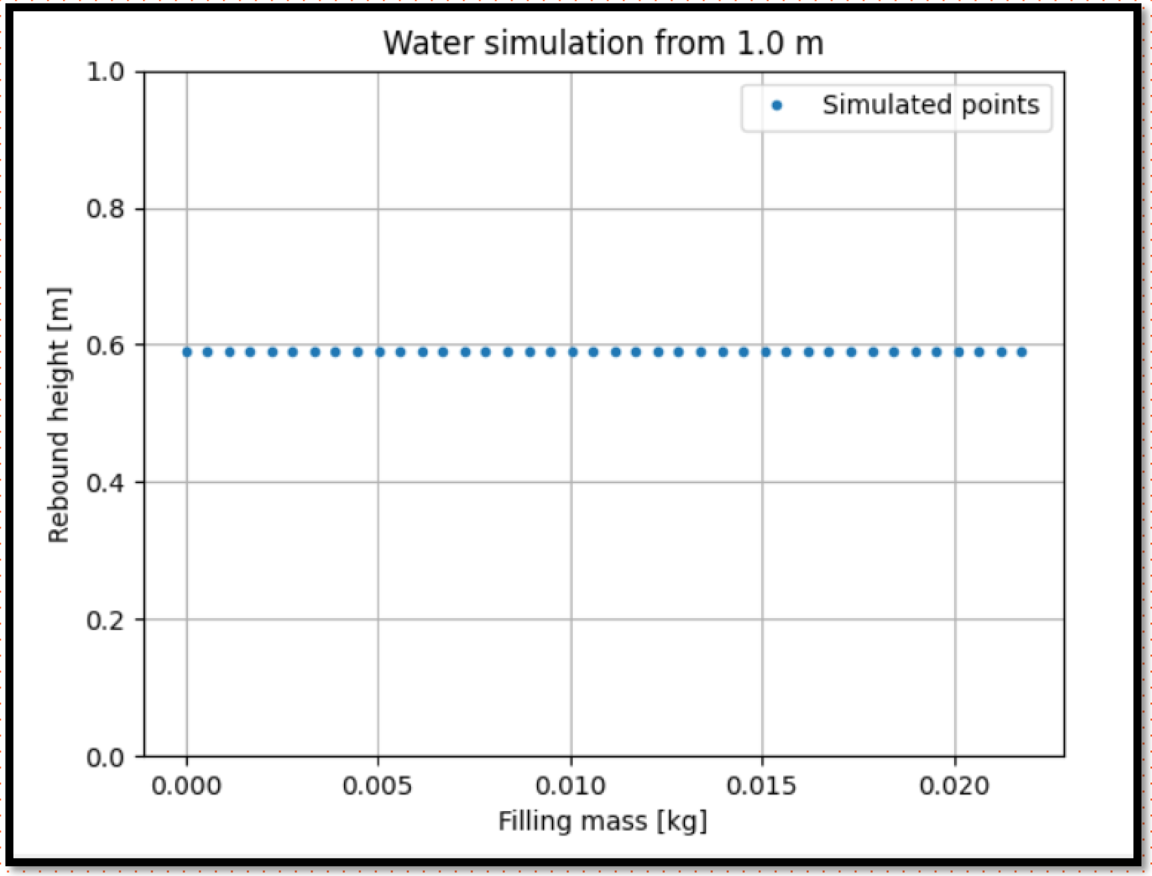


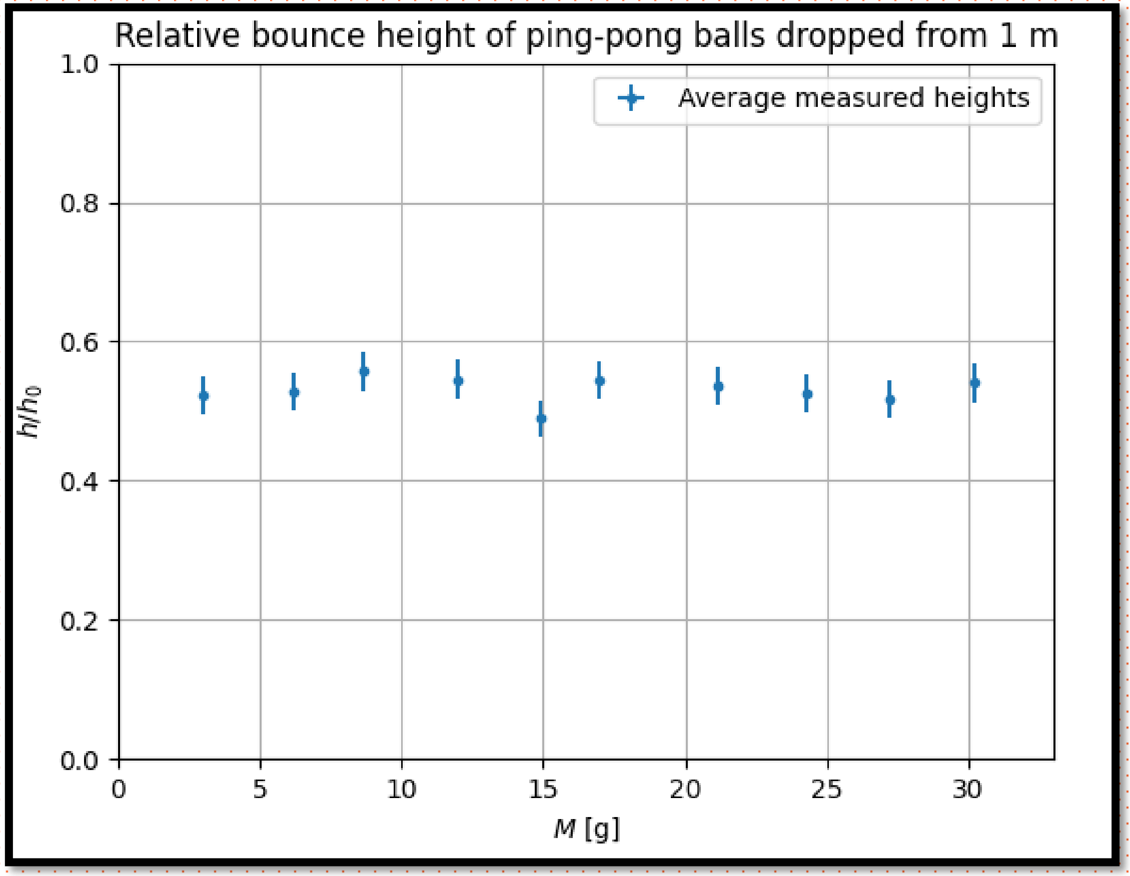


Filling mass and ball size



Simulation for water

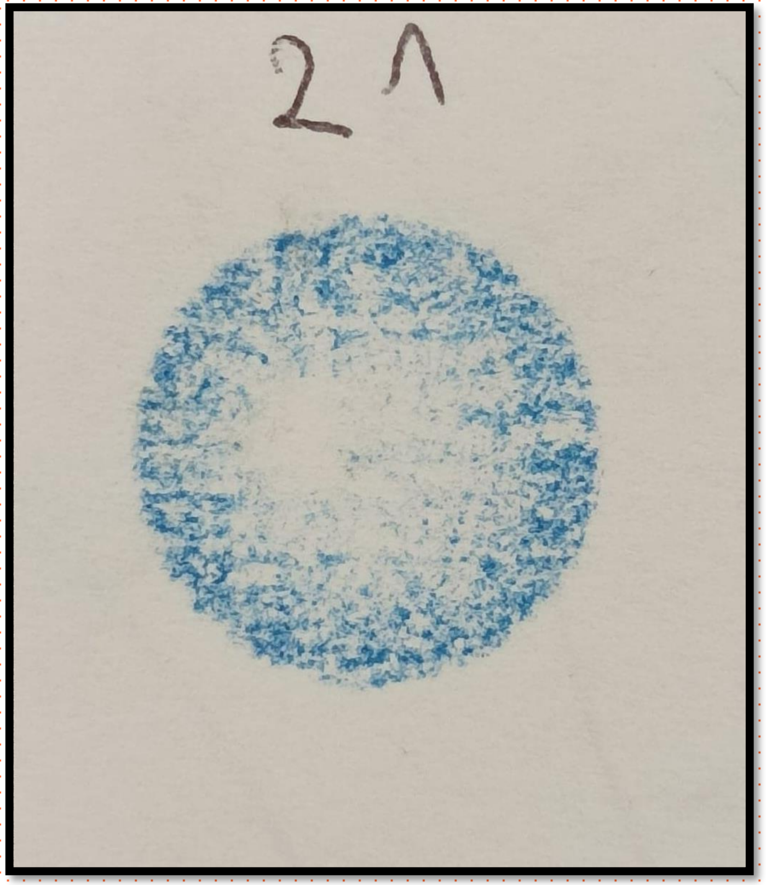


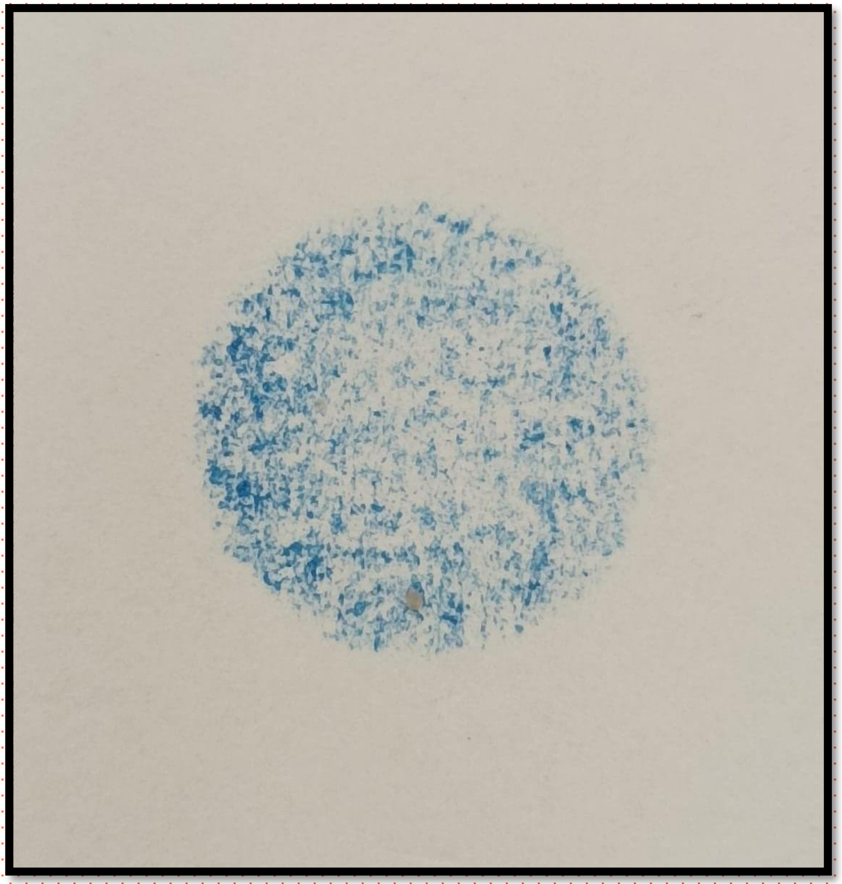


58.7% of water energy conserved

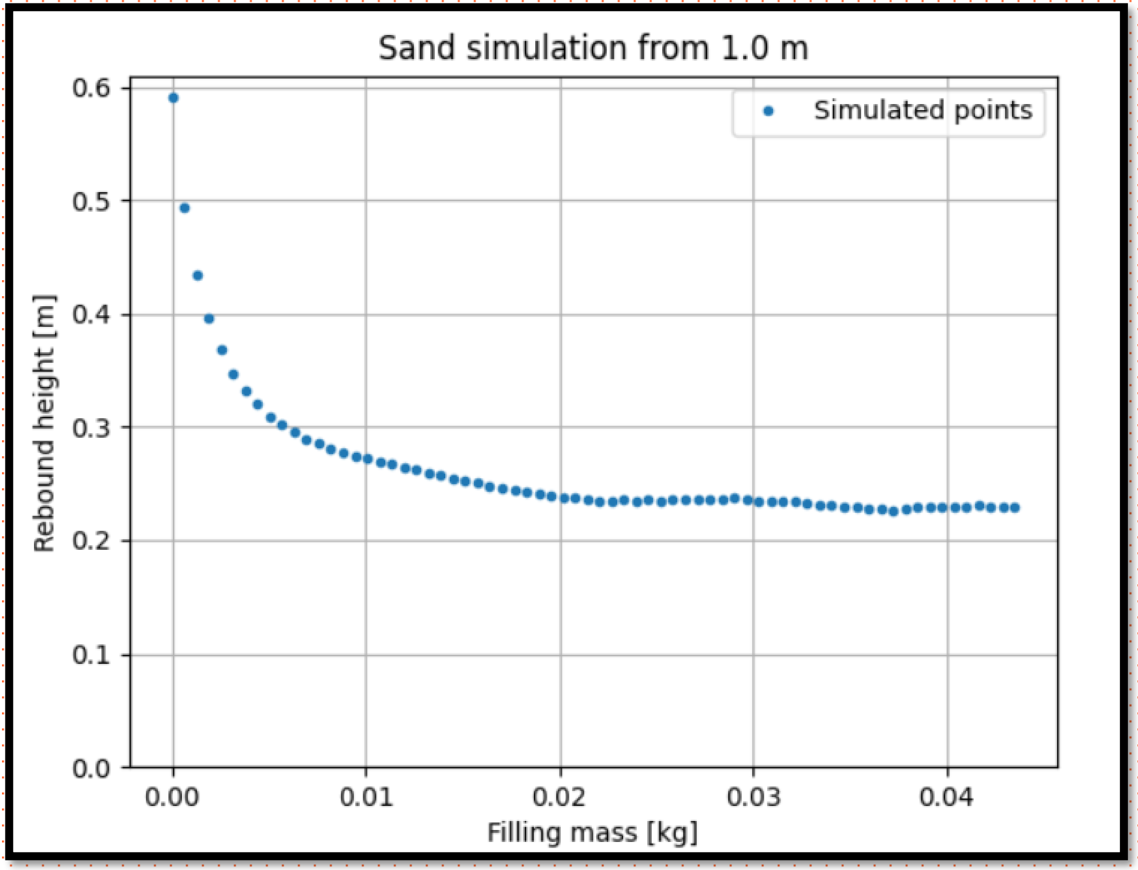
Differences between water and sand

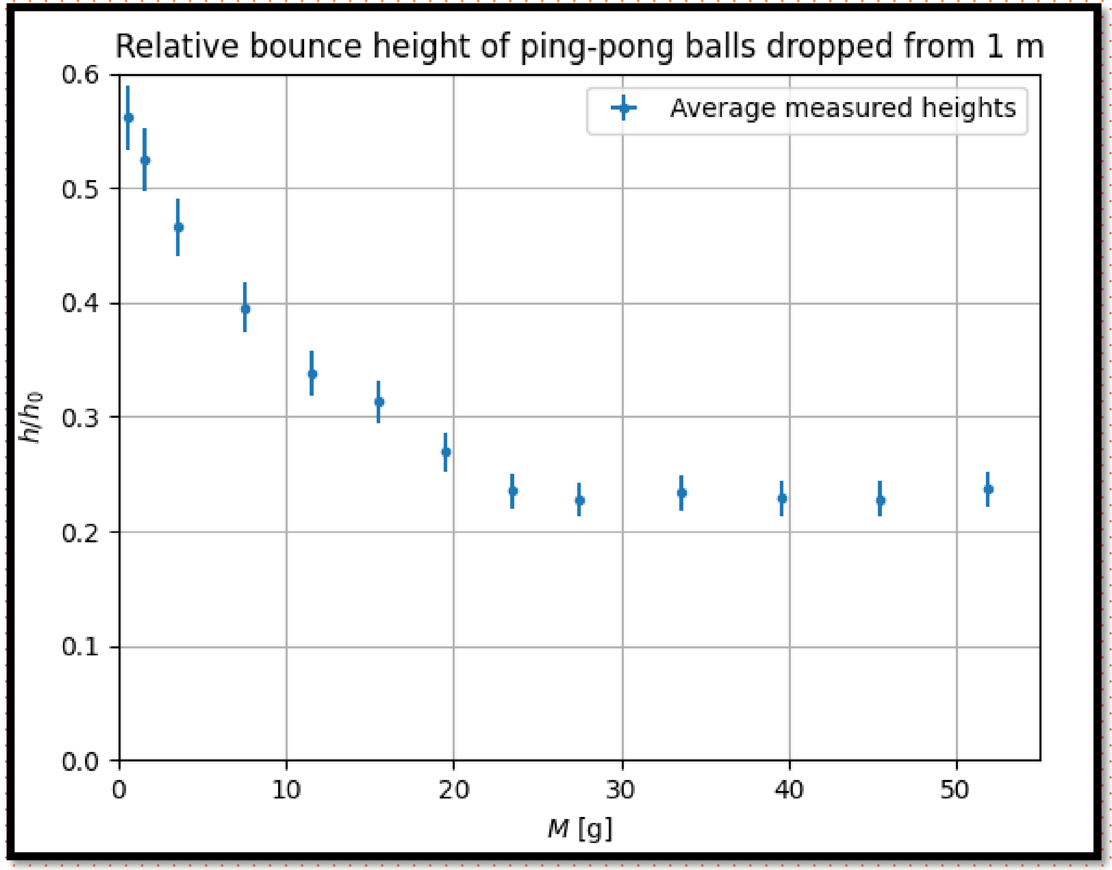
Ball	Retained Energy
Ping-pong	0.587
Water	0.587
Sand	0.2





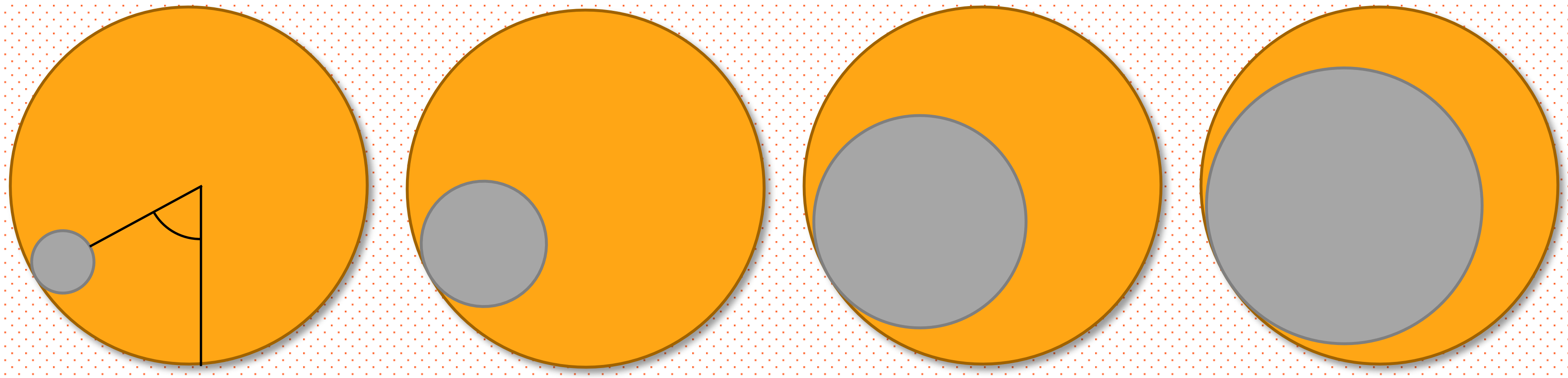
Simulation for sand



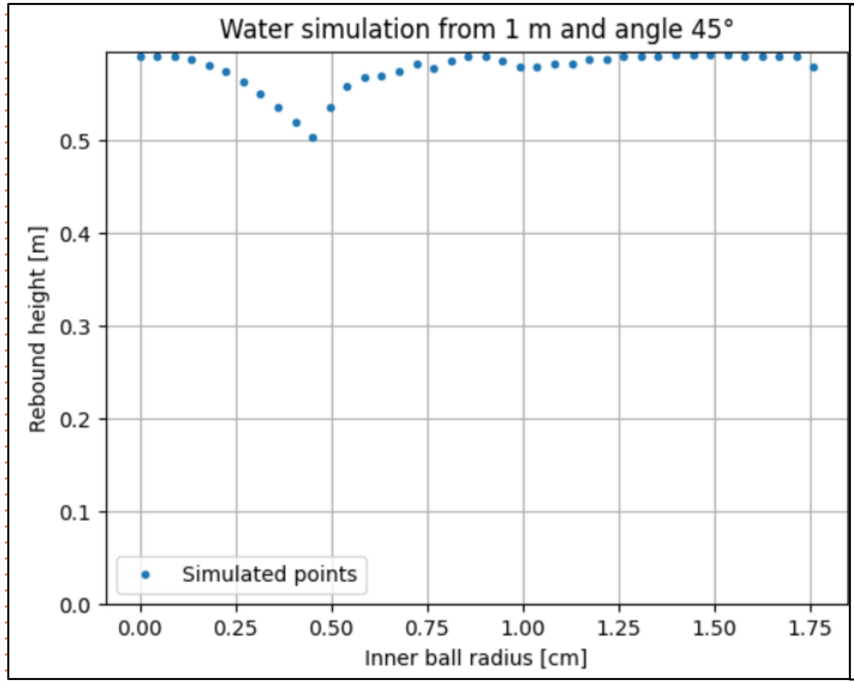


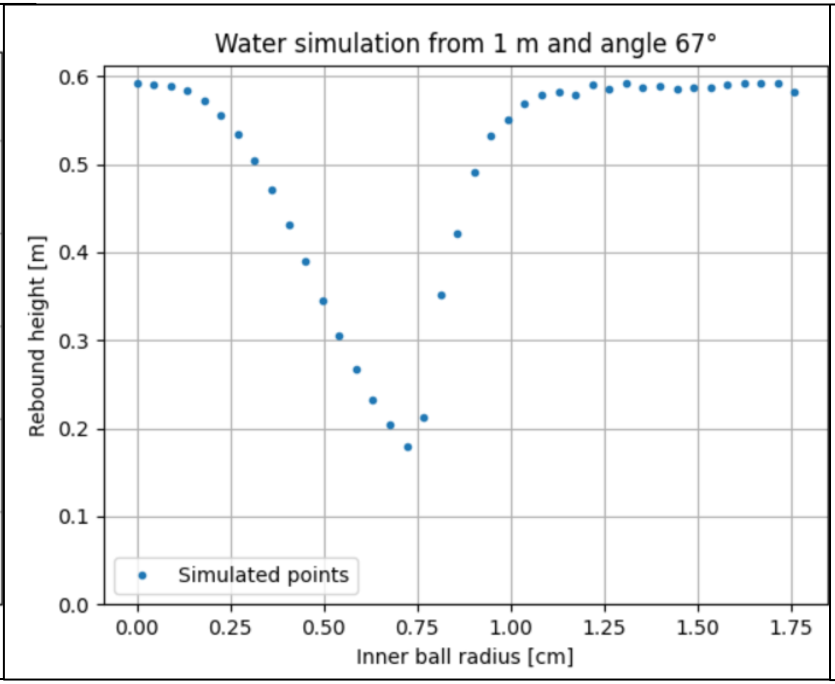
Fitted: 20% of sand energy conserved

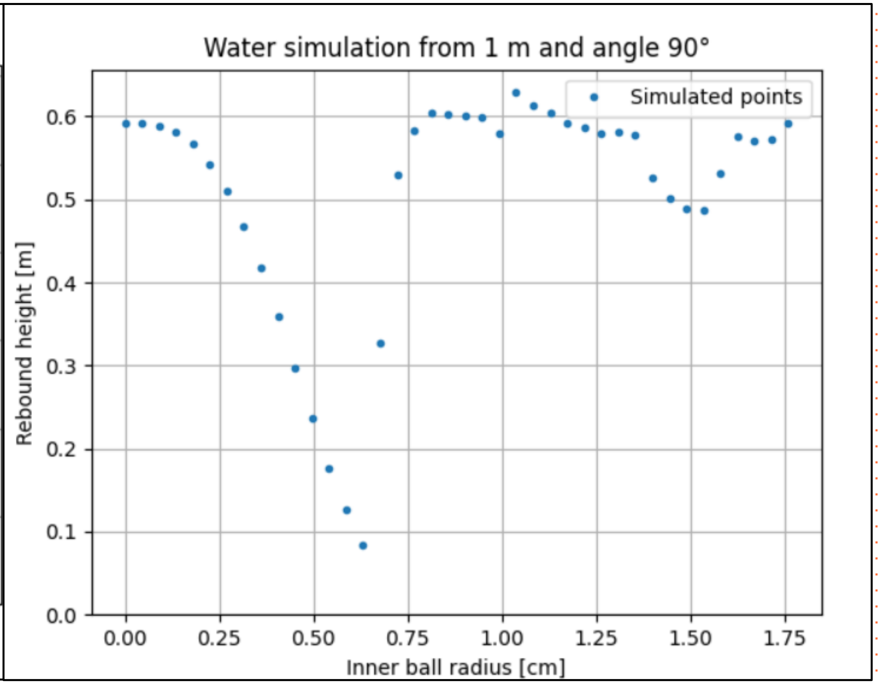
Initial angle



Different angles - water

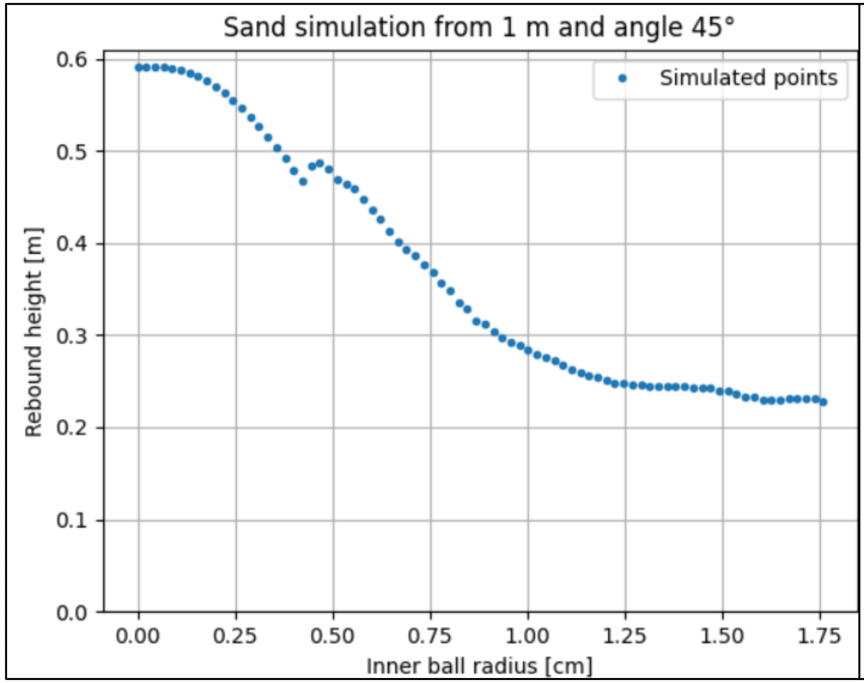


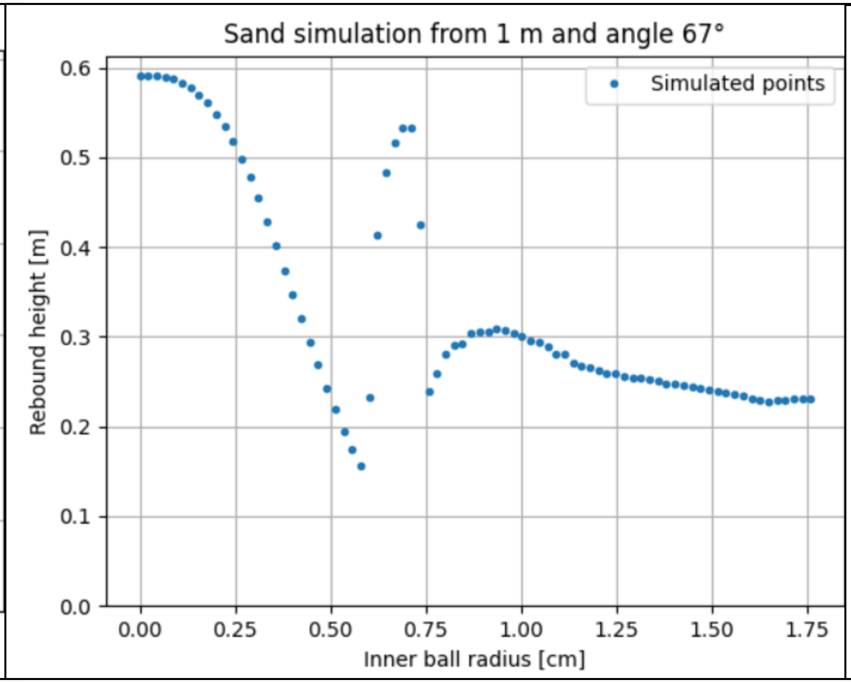


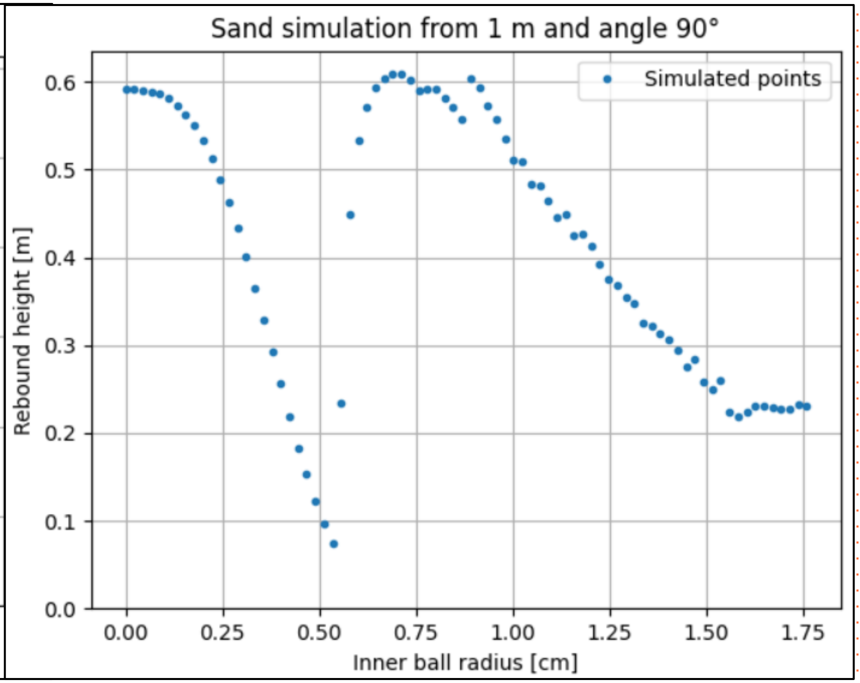


Function of inner ball radius – not filling mass

Different angles - sand

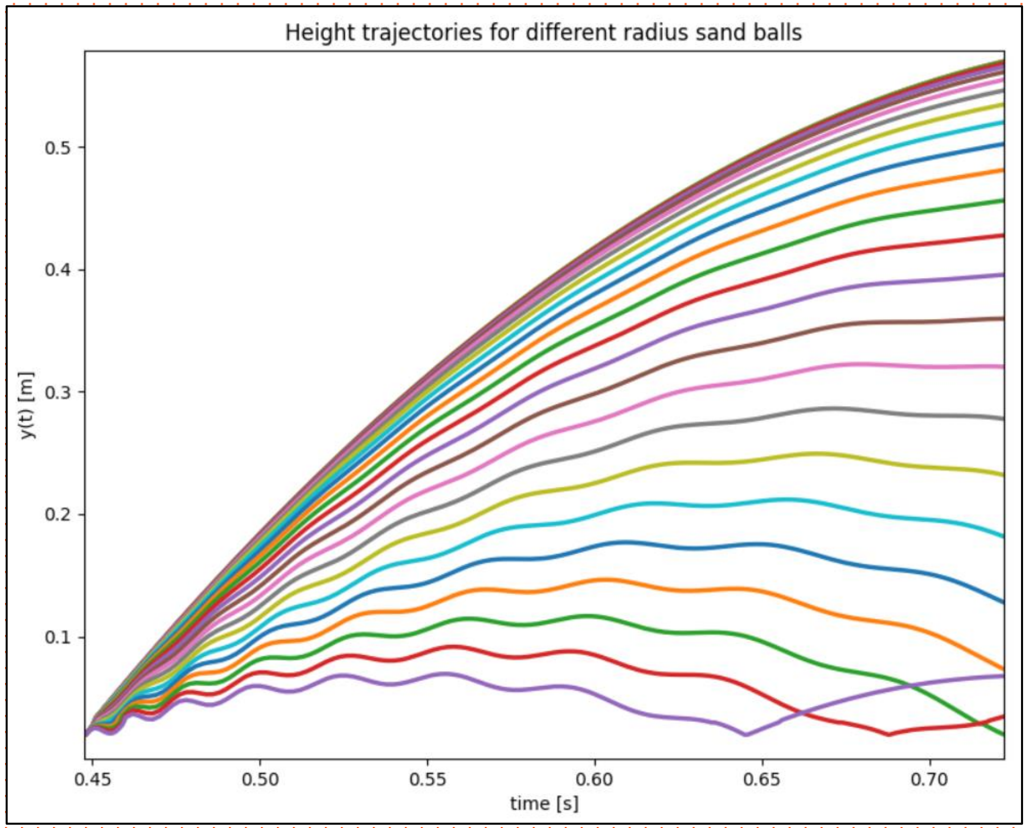


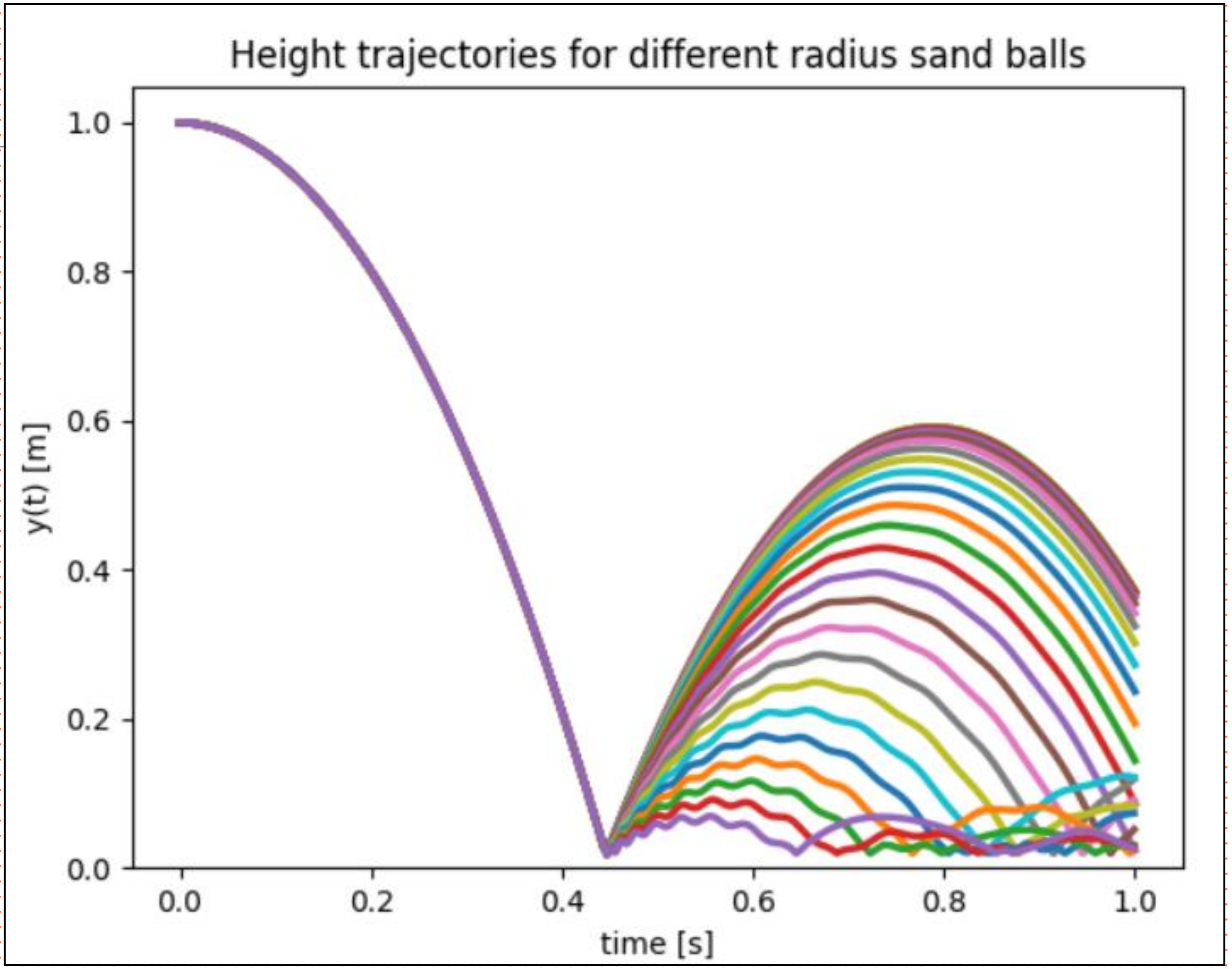




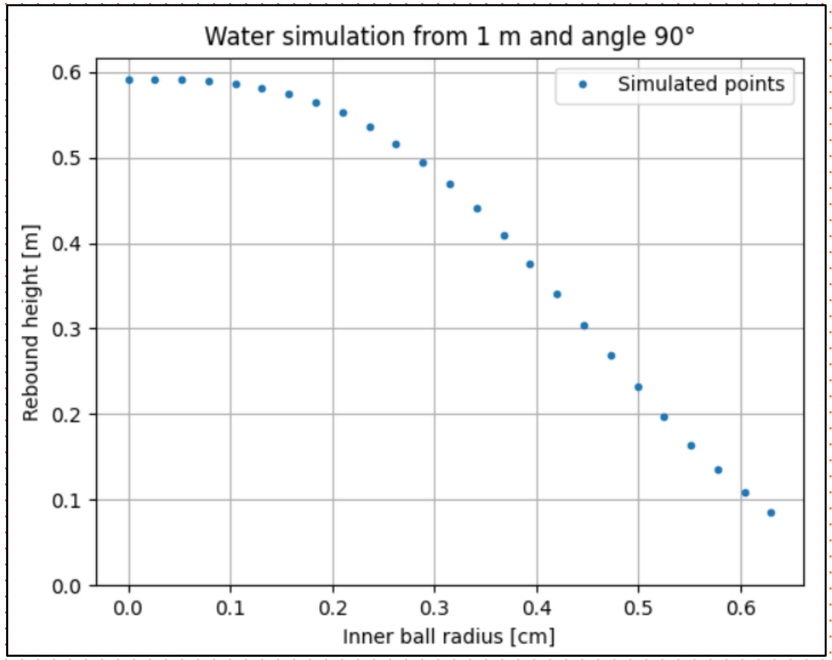
Function of inner ball radius – not filling mass

Sand

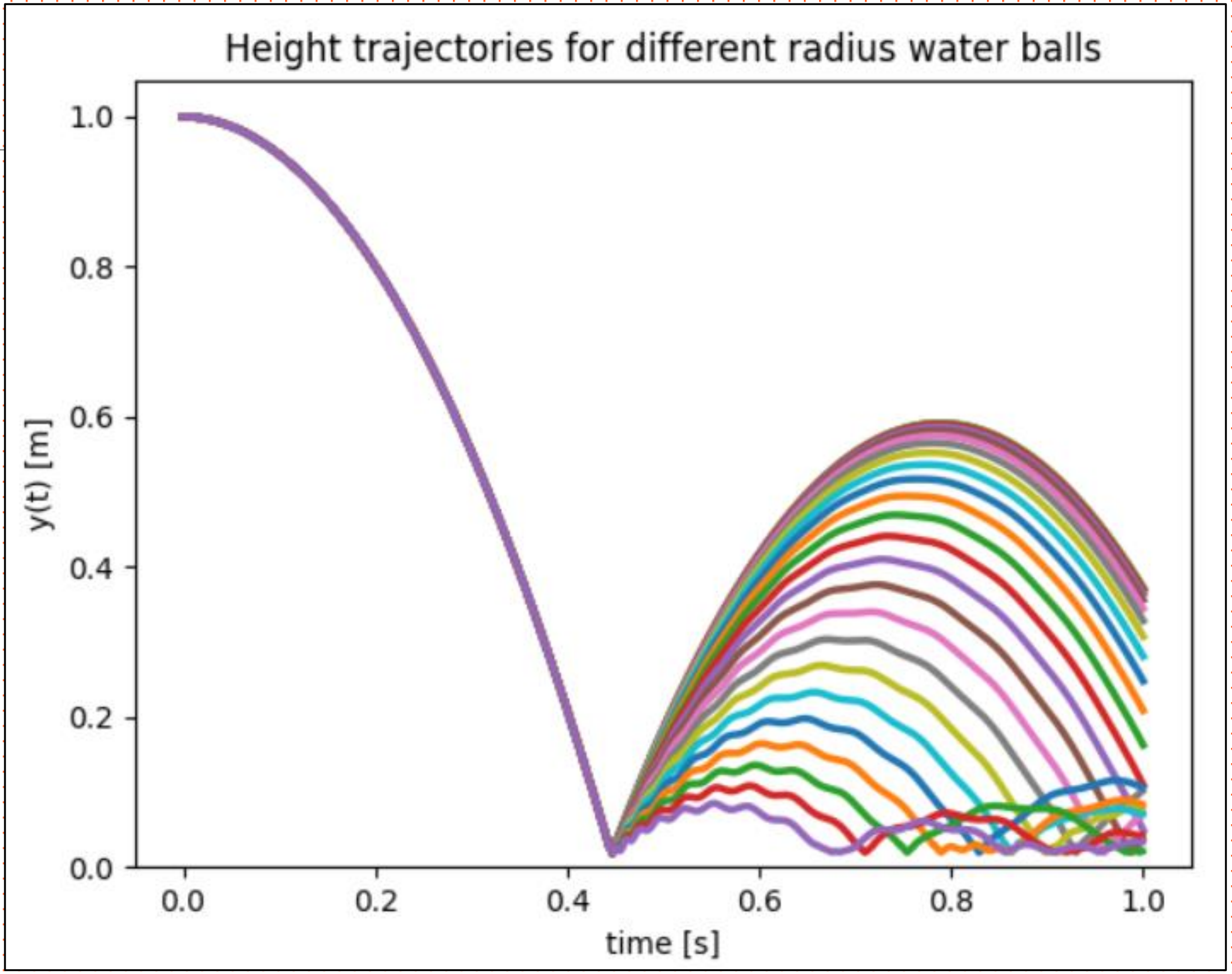

Height trajectories for different radius sand balls
0.5
0.4
0.3
0.2
0.1
y(t) [m]
0.45
0.50
0.55
0.60
0.65
0.70
time [s]


Height trajectories for different radius sand balls
1.0
0.8
0.6
0.4
0.2
0.0
y(t) [m]
0.0
0.2
0.4
0.6
0.8
1.0
time [s]

Water



Water simulation from 1 m and angle 90°
Simulated points
Rebound height [m]
Inner ball radius [cm]
0.0
0.1
0.2
0.3
0.4
0.5
0.6



Height trajectories for different radius water balls
y(t) [m]
time [s]
0.0
0.2
0.4
0.6
0.8
1.0

Conclusions

- We proved that provided the right setup the height of the bounce can be the same for a half filled ball
- We measured how the height depends on the mass of the filling, the difference between liquid and a granular material
- We proved that the damping is a result of symmetry breakage in initial conditions and explained the movement of filling during impact
- We provided a useful analogy with a stiff ball inside the ping-pong ball and checked how it corelates to the initial problem

References

1. *Street hockey ball,* U.S. patent 6,645,098 (11 November 2003)

2. T. W. Killian, R. A. Klaus, T. T. Truscott, *Rebound and jet formation of a fluid-filled sphere*

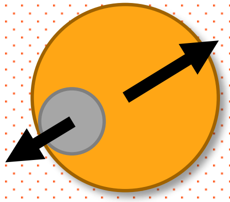
3. F. Pacheco-Va´zquez , S. Dorbolo*, Rebound of a confined granular material: combination of a bouncing ball and a granular damper*

4. *https://www.pyimagesearch.com/2015/09/14/ball-tracking-with-opencv/*

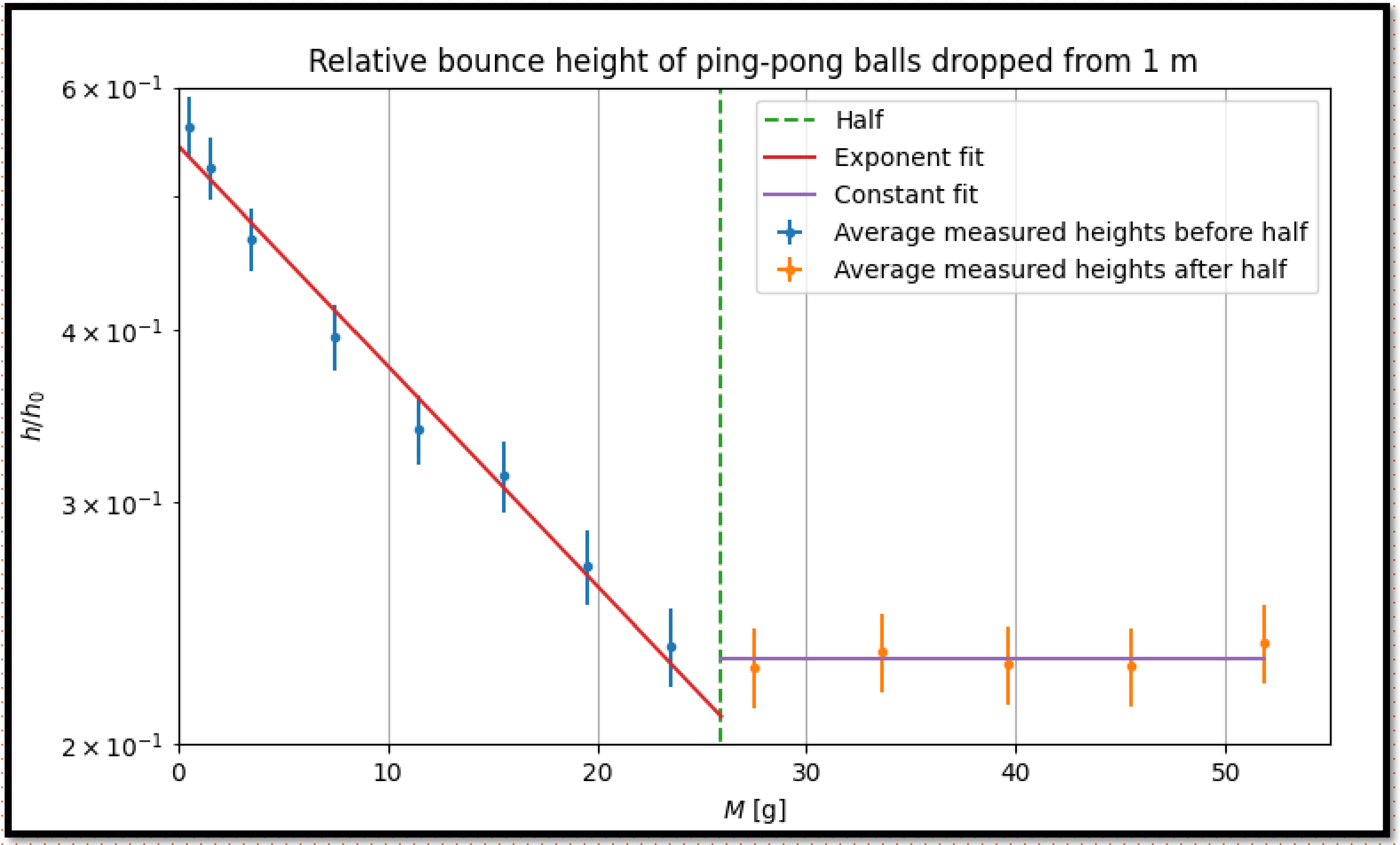
5. L. Pauchard, S. Rica 1998, *Physics of a ‚ping-pong' ball*

The Simulation

- The balls are in constant gravitational field
- Ping-pong ball feels k*(radius – y) force (while y<radius and v<0), where k=15000 (to match dynamometer measurement), **but** feels 0.587*k*(radius-y) while v>0
- The inner balls bounce in one time step, loosing 0.587 (water) or 0.2 (sand) of its energy
- The balls collision is calculated as one of two bodies with some relative radial velocities, with masses 2.5g for the ping-pong ball and volume*density for the inner ball
  and the CoR 0.75

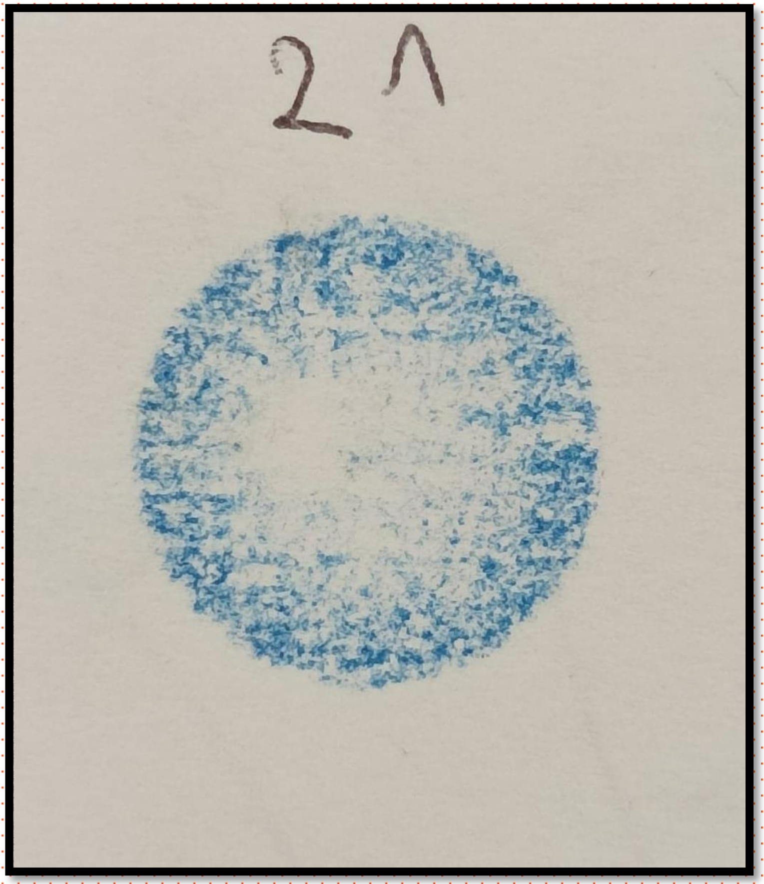


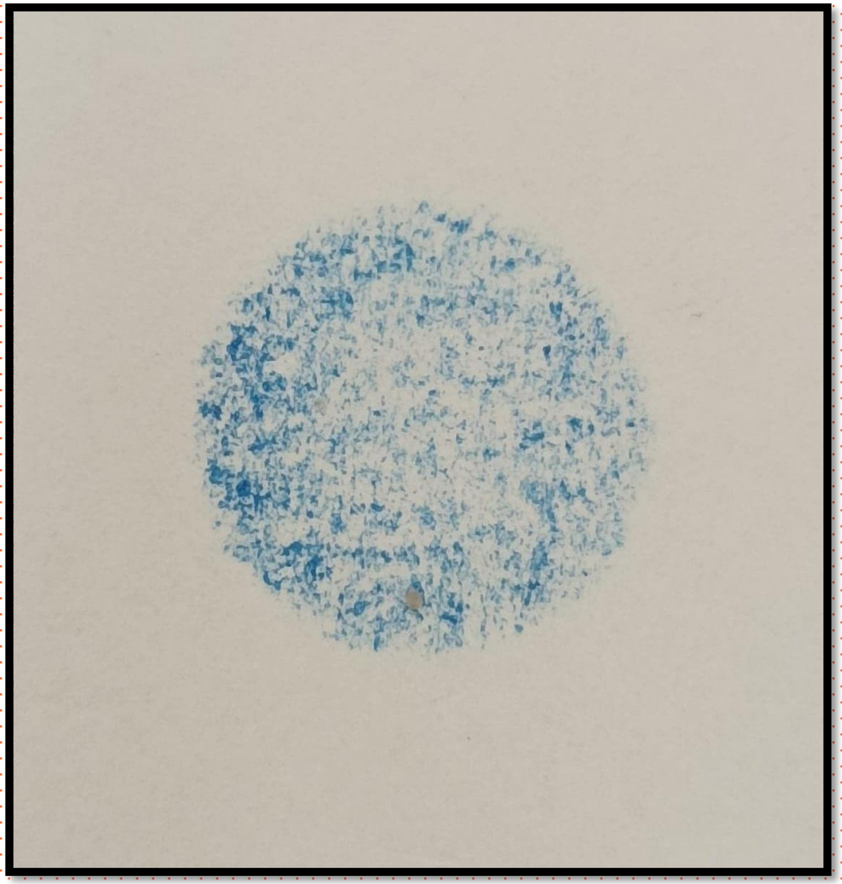
- The model is two dimensional, but mass scales with density times volume

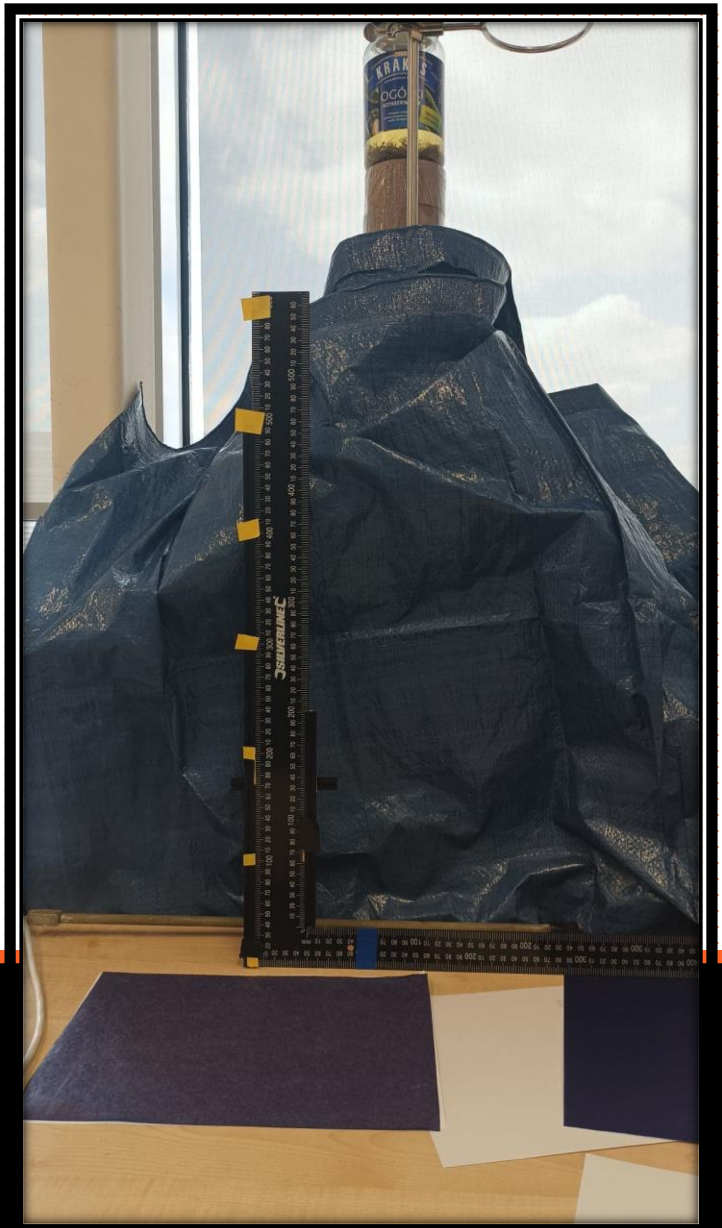


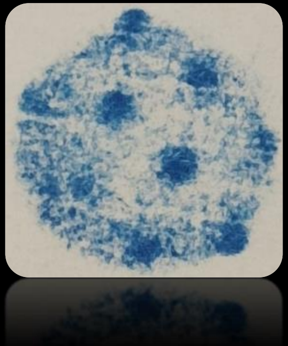
Results in logarithmic scale

Exponential fit: 0.587*exp(-0.48M)





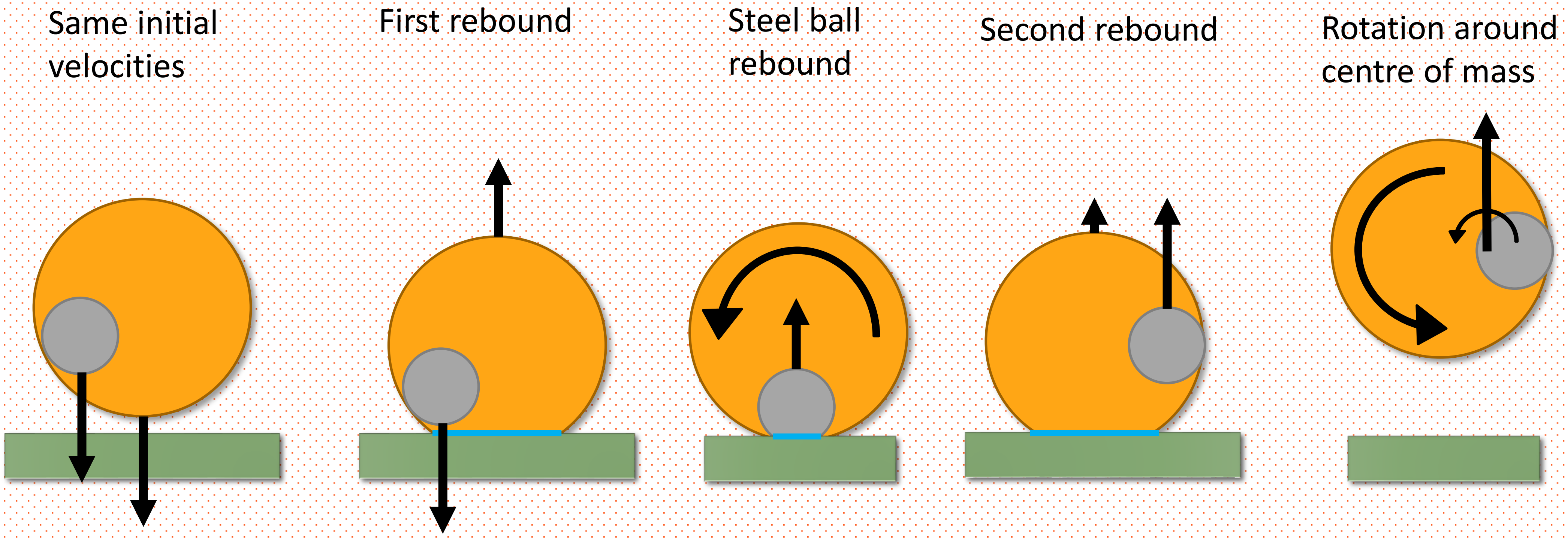




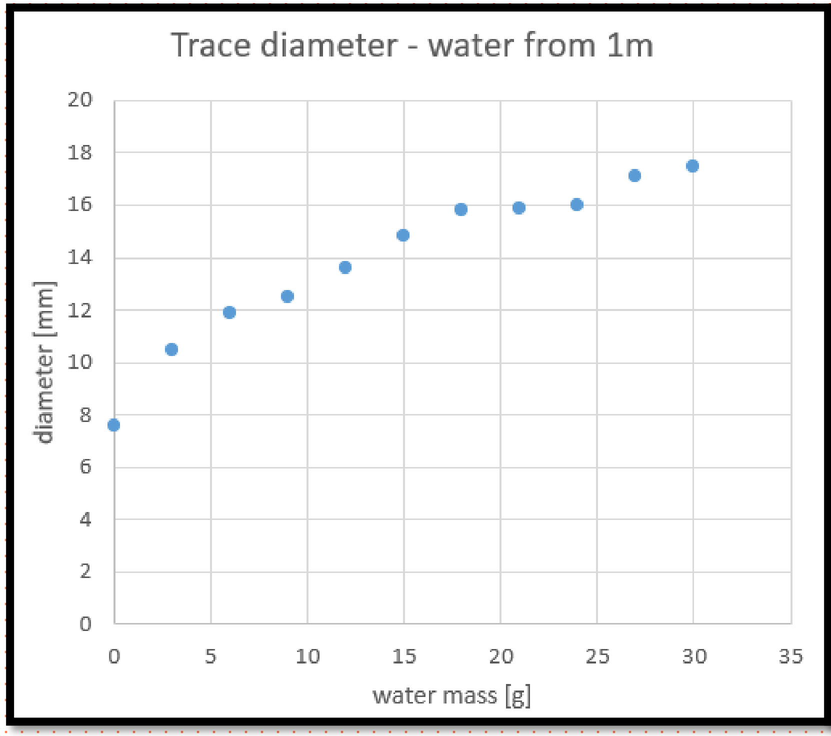
Tracing paper

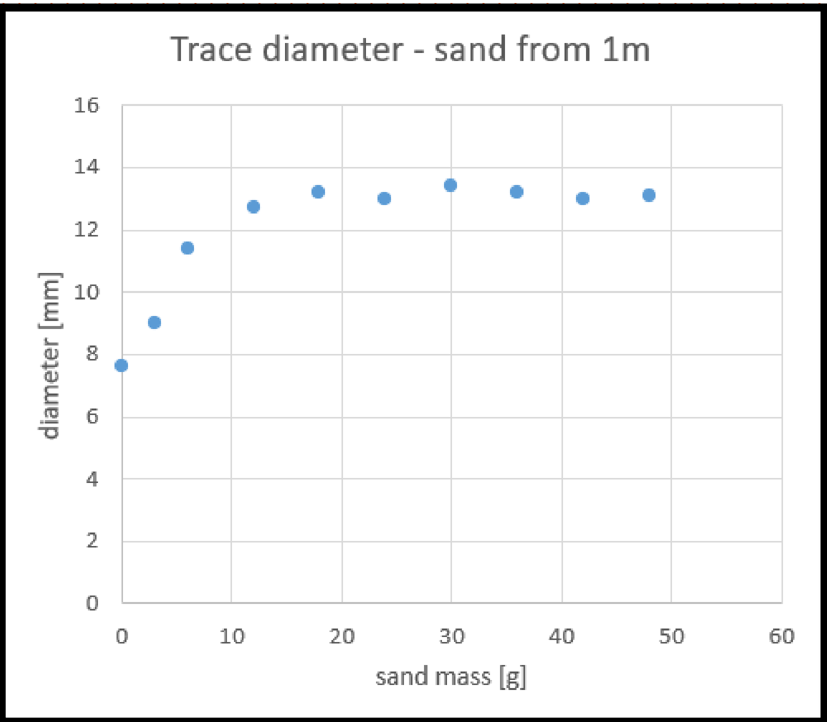
Double rebound

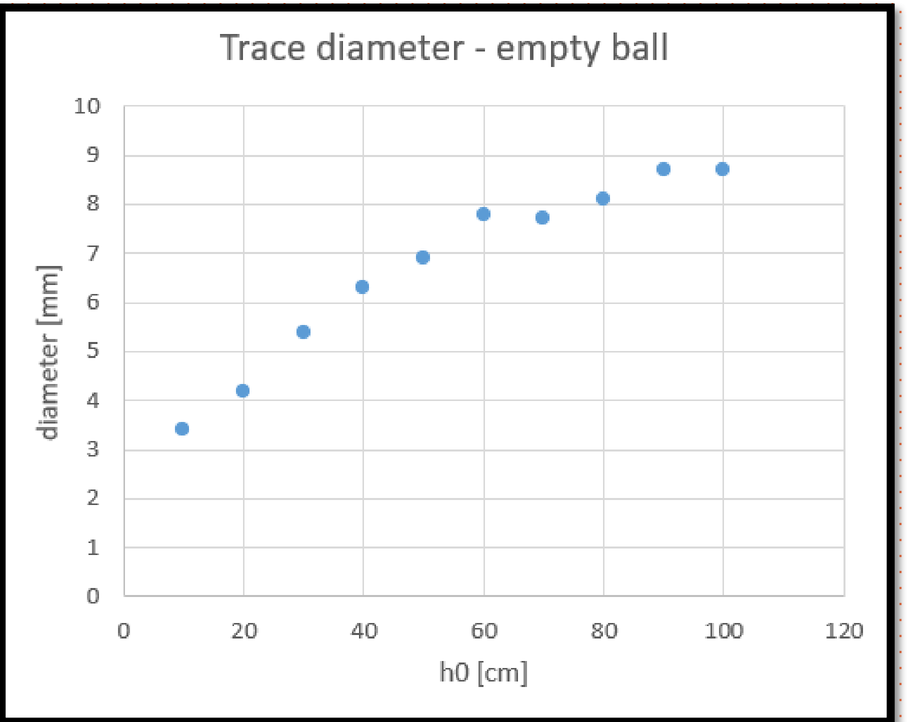
Steel ball inside the sphere



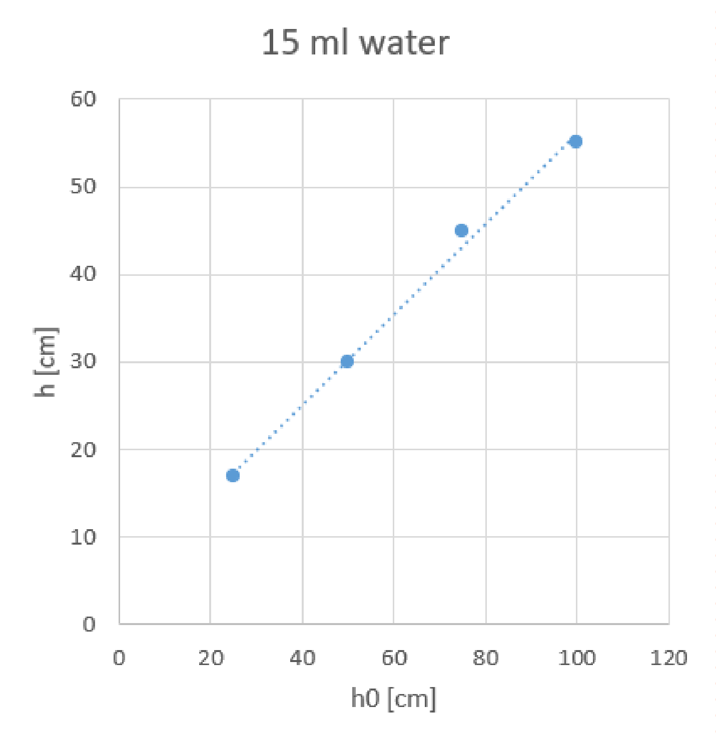
Trace diameter

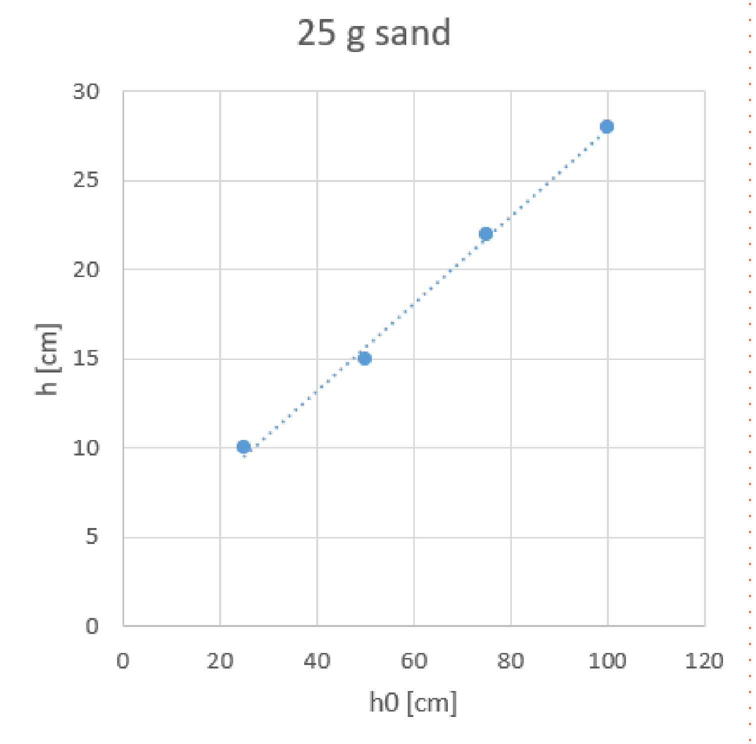


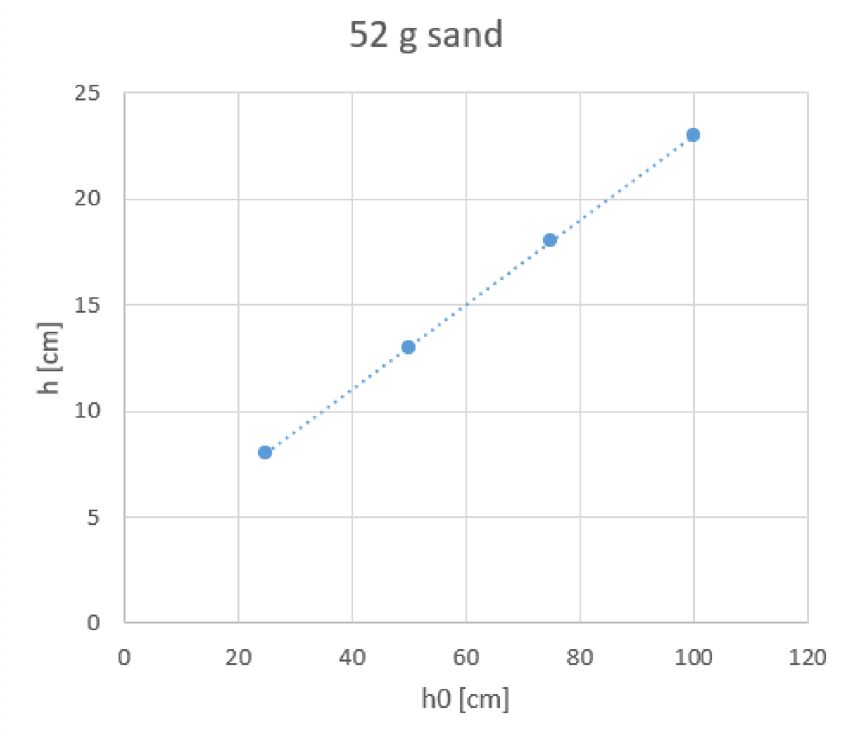




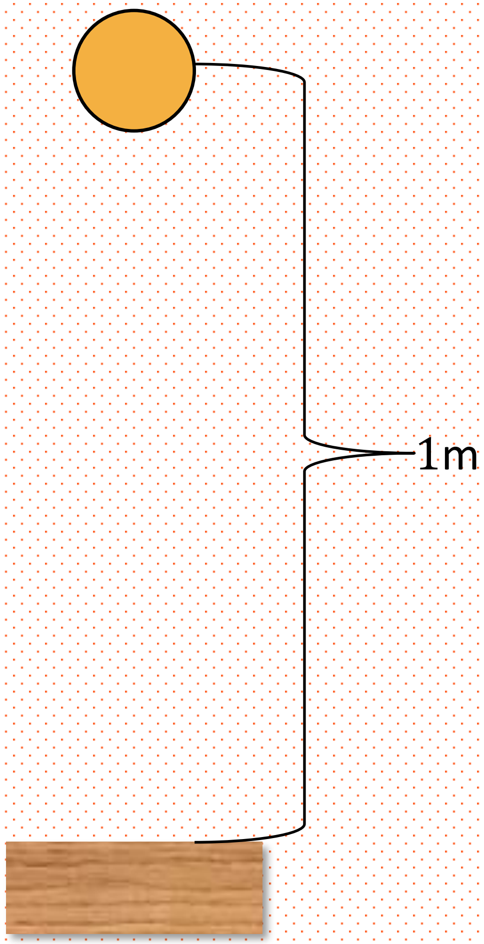
Initial height







$m = (2.55 \pm 0.01)\mathrm{g}$



$$\left\langle \frac{h}{h_0} \right\rangle = 0.587$$

$$\sigma = 0.0126$$

$$\delta h = \frac{\sigma}{\sqrt{n}} = \frac{0.0126}{\sqrt{21}} \approx 0.003$$

$$\alpha = \frac{E}{E_0} = \frac{h}{h_0} = (58.7 \pm 0.3) \cdot 10^{-2}$$

Limits of our simulation