Microgravity

Space Technology I

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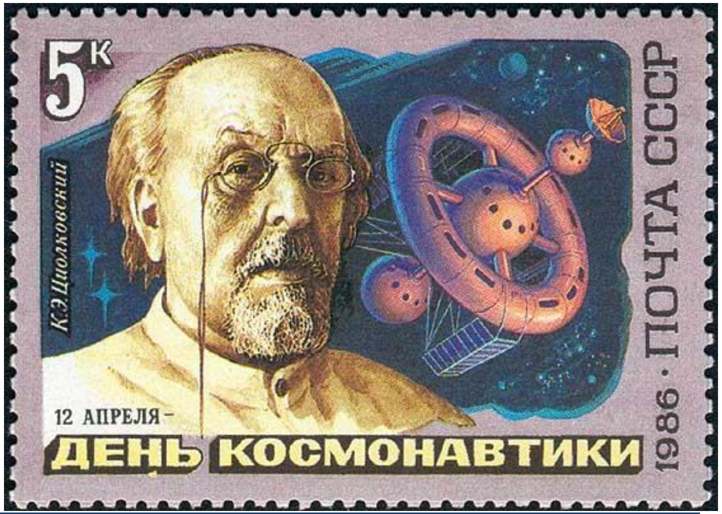
Topics

- Space exploration – brief introduction, space race
- Gravity (basic physics principles)
- How to perform microgravity research?
- Physical phenomena affected by gravity
- Plants in space/ challenges in microgravity
- One-year Mission (microgravity what changes in the human body)

Space Exploration

"*Earth is the cradle of humanity, but one cannot remain in the cradle forever.*"
(Konstantin Tsiolkovsky)

One of the fathers of rocketry and cosmonautics, along with Goddard and Oberth



Space Exploration

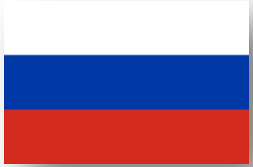
Historical context: World War II, post-war, Cold war

"Control of space means control of the world"

"From space, the masters of infinity would have the power to control the earth's weather, to cause drought and flood, to change the tides and raise the levels of the sea, to divert the gulf stream and change temperate climates to frigid".

Lyndon B. Johnson

Space Race



Russia

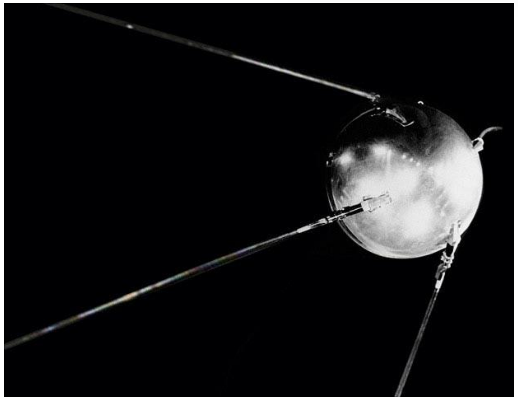
Sputnik I (first artificial satellite)

Ball (58 cm diameter 4 antennas)

Mass: 83,6 Kg

Launched from Baikonur with R-7

(R-7 the world's first intercontinental ballistic missile)



Sputnik II

It took the 1st living being to enter orbit: ***Laika***

Mass: 500 kg

Space Race

USA's reaction

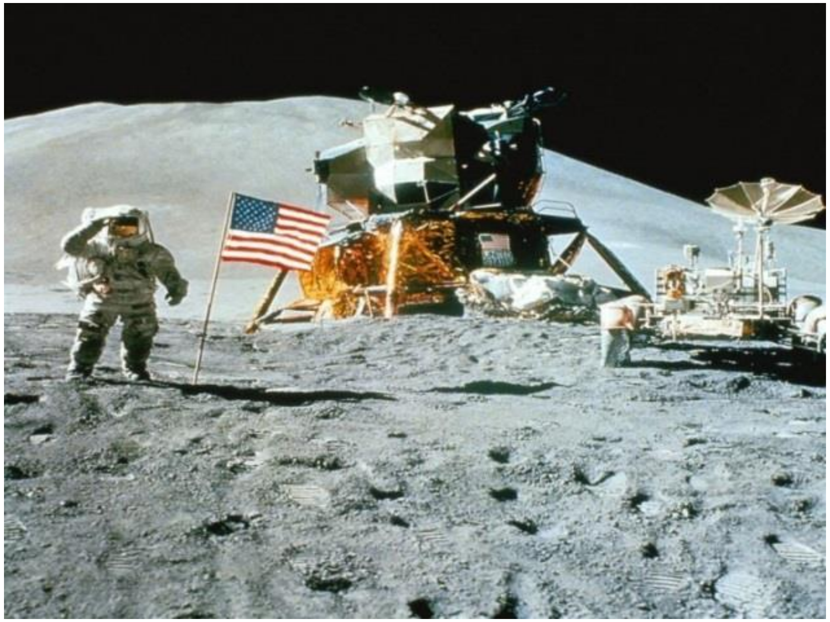
- *Explorer I*

(discovered the Van Allen Belt)

- NASA was founded (1958)

- Moon exploration

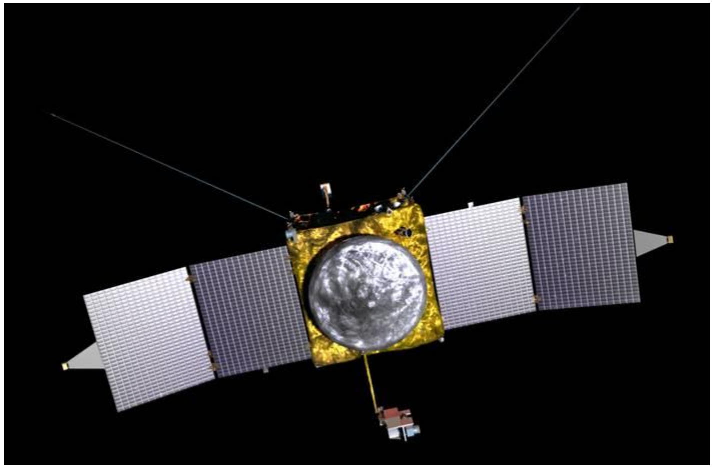
Man on the Moon (1969)



Planetary missions

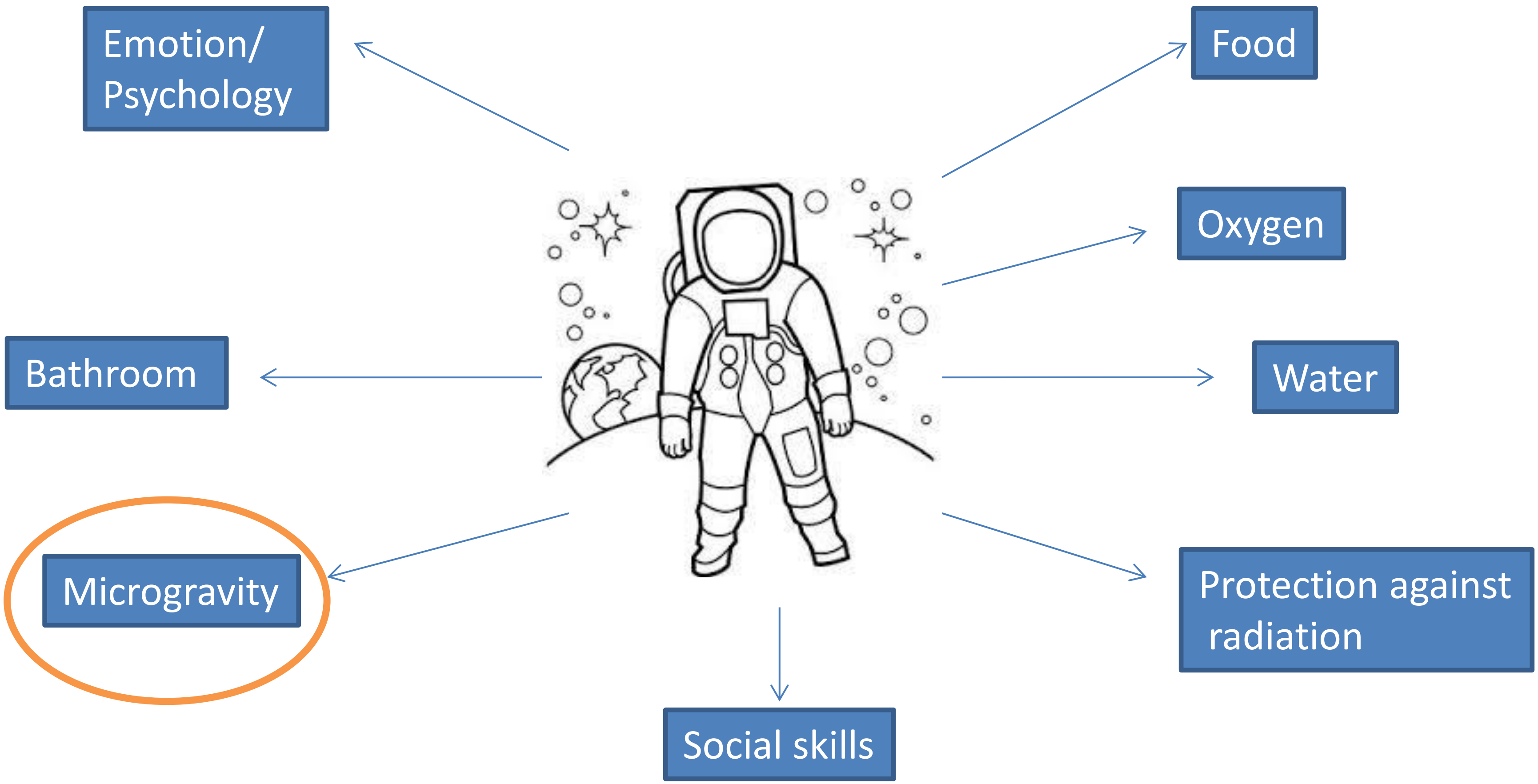
Mars: 7 missions to Mars
Jupiter: 6 spacecraft launched to explore Jupiter
Saturn: 4 spacecraft visited Saturn

Curiosity on Mars - NASA



Mars orbiter - NASA

Travel to Mars



Microgravity

Microgravity: "micro" comes from the Greek word **mikros**, meaning "small". In metric terms, the prefix means "one part in a million" (0.000001).

Microgravity Research: very low **g** conditions ($<10^{-4}$ g)

How to perform Microgravity Research?

Drop Tower - Bremen

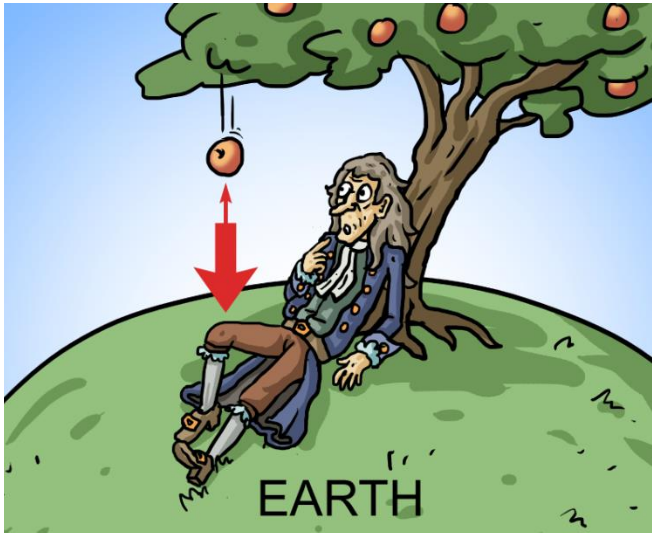
Parabolic flight

International Space Station

Law of gravity

‘A particle attracts every other particle in the universe using a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between them’

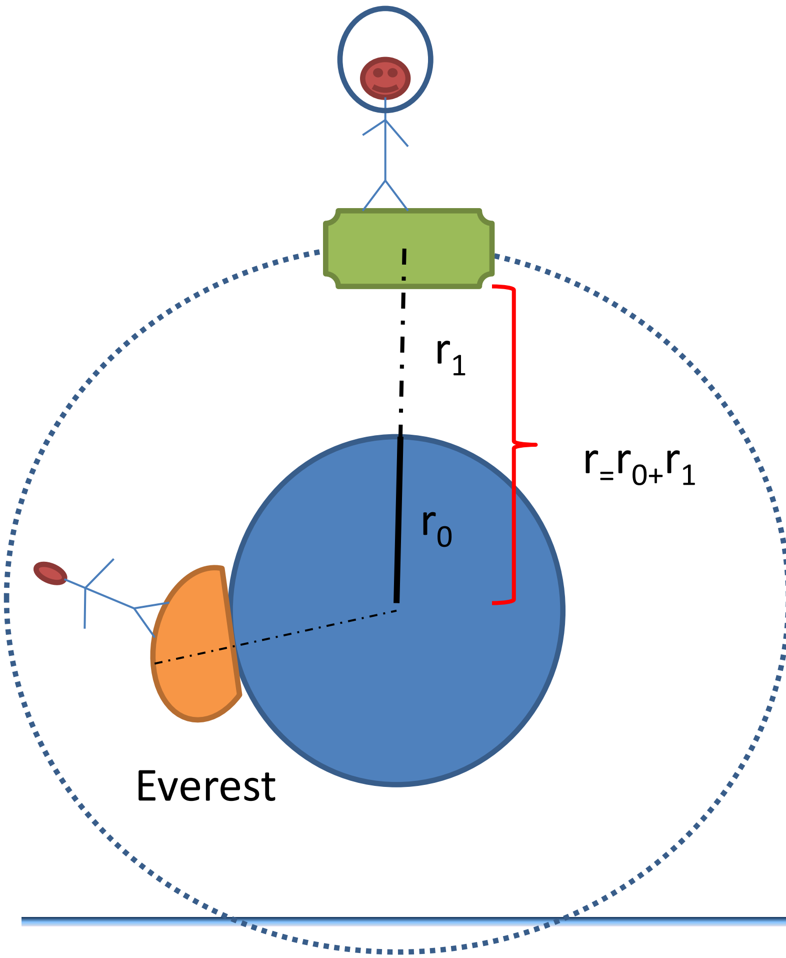
$$F_g = G\frac{Mm}{r^2}$$



G= The universal gravitational constant

6,67x 10^{11} $m^3kg^{-1}s^{-2}$

Gravitational acceleration



$$F_g = \frac{GMm}{r^2} \qquad F_g = ma_g$$

Combining the two equations

$$ma_g = \frac{GMm}{r^2} \qquad a_g = g$$

$$\boxed{g(r) = \frac{GM}{r^2}}$$

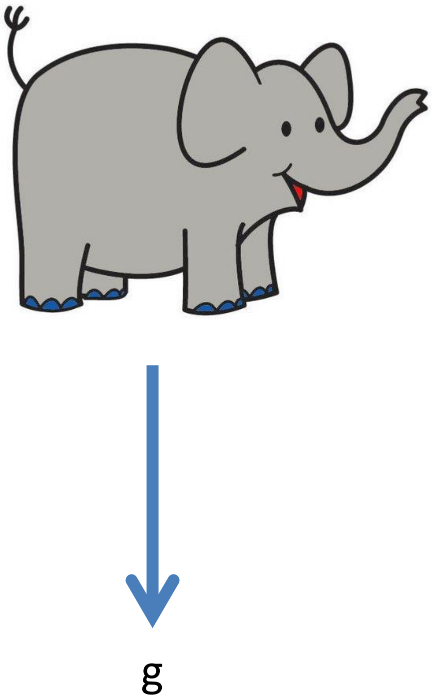
g does not dependent on the mass of the object

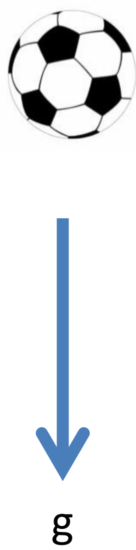
$g_{Earth} = 9.81\ m/s^2$

'Average' acceleration due to gravity on Earth

Considering Earth a sphere

Free Fall (weightlessness)





No air resistance

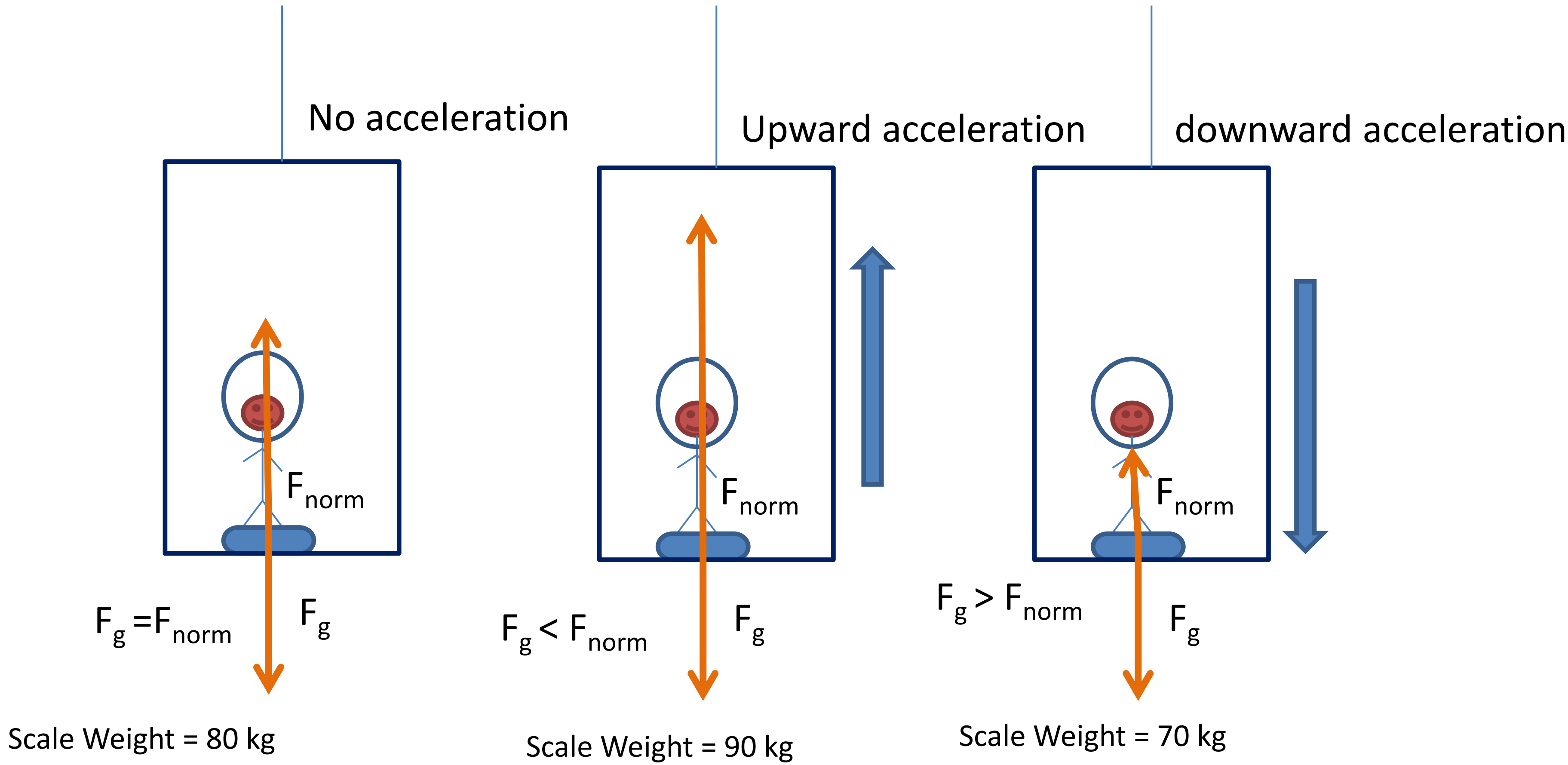
$a = g = 9.81\ m/s^2$

The object is only feeling the force of gravity!
(no contact forces acting)

Mass and shape do not affect the motion.

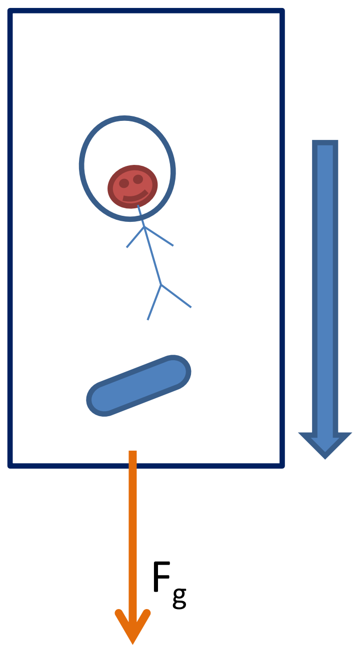
All objects fall at the same rate in a vacuum.
Galileo

An astronaut in an elevator upon a scale



The scale noes not measure your weight but the contact forces being applied to your body.

Downward acceleration = g = 9,81 m/s^2



$F_{norm} = 0$

Scale Weight = 0

Free fall – weightlessness

The astronaut in the falling elevator feels weightless because there are no external forces pushing or pulling his body. He is in a state of free fall.

Drop Tower

Drop capsule

- 146 meters (Bremen)
- Provides 4.74 or 9.3 seconds of microgravity
- Uses high-performance pumps to remove the air
- A capsule is dropped inside the drop tower and experiences a free fall of 110 m for 4.74 seconds. The 2-metre long capsule is caught in a 10 m deep container filled with polystyrene balls.

Drop Tower - Bremen

Drop Tower

Time in free fall:

Tower is 146m, effective height = 110m

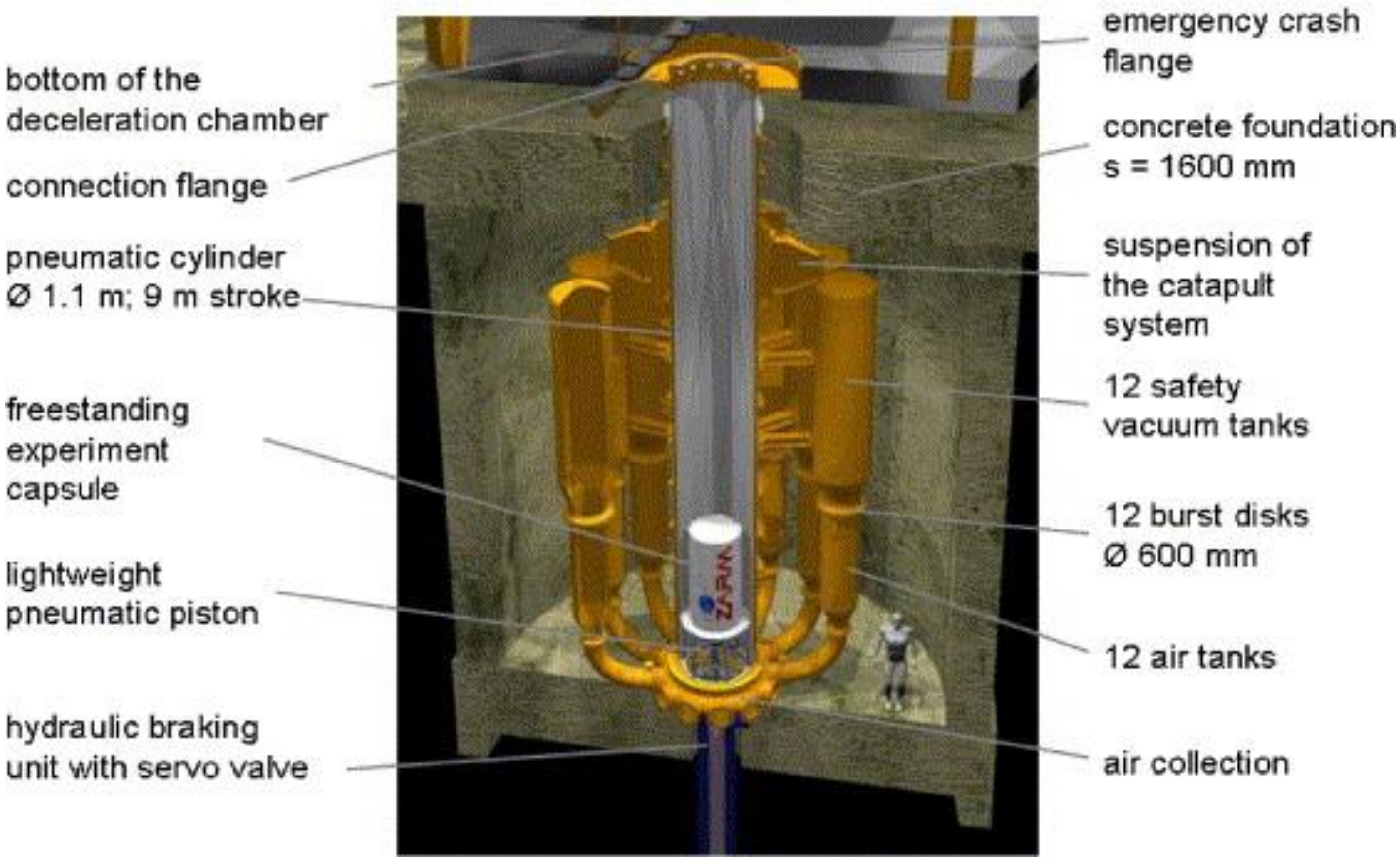
$d = g\,t^2/2$ d= height

$$t = \sqrt{\frac{2 * 110\ m}{9.81\ m/s^2}}$$

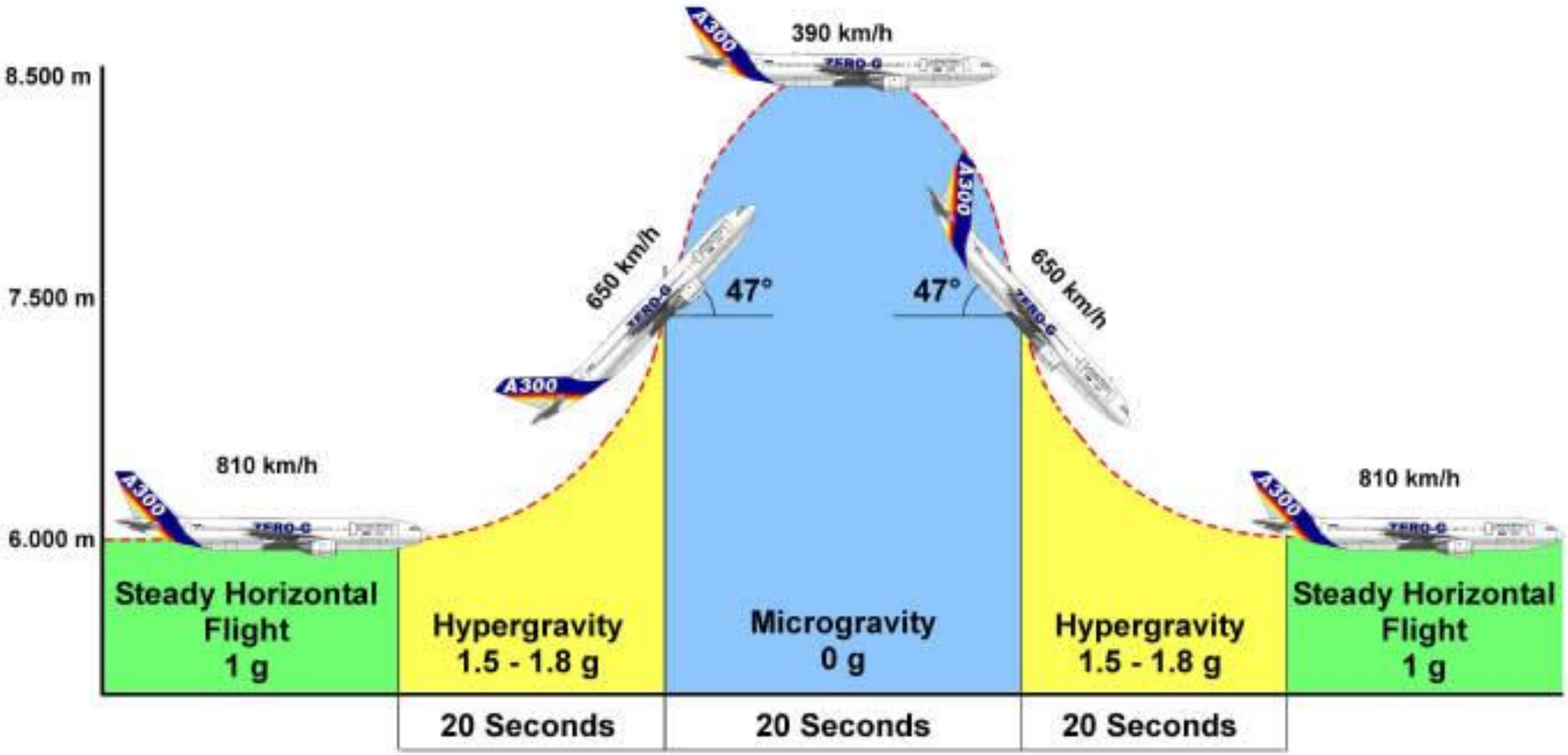
t ≈ 4.74 seconds

Drop Tower – Catapult system

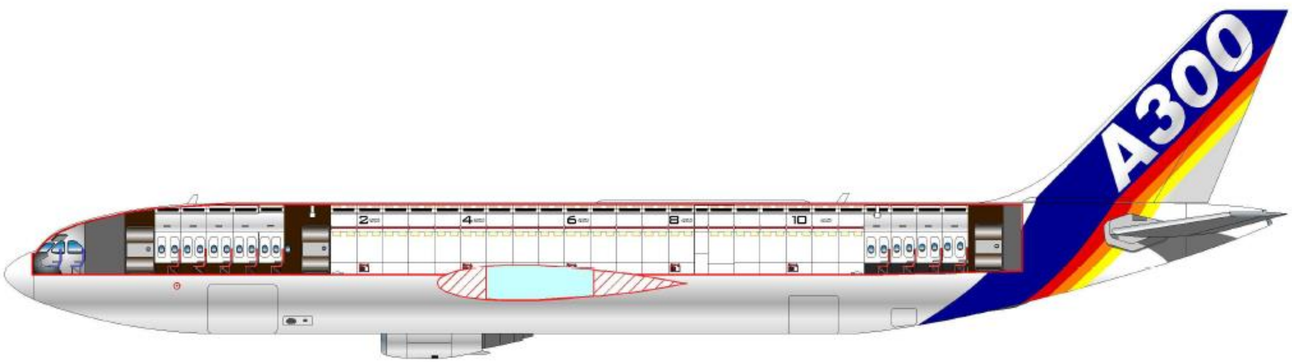
The Catapult System

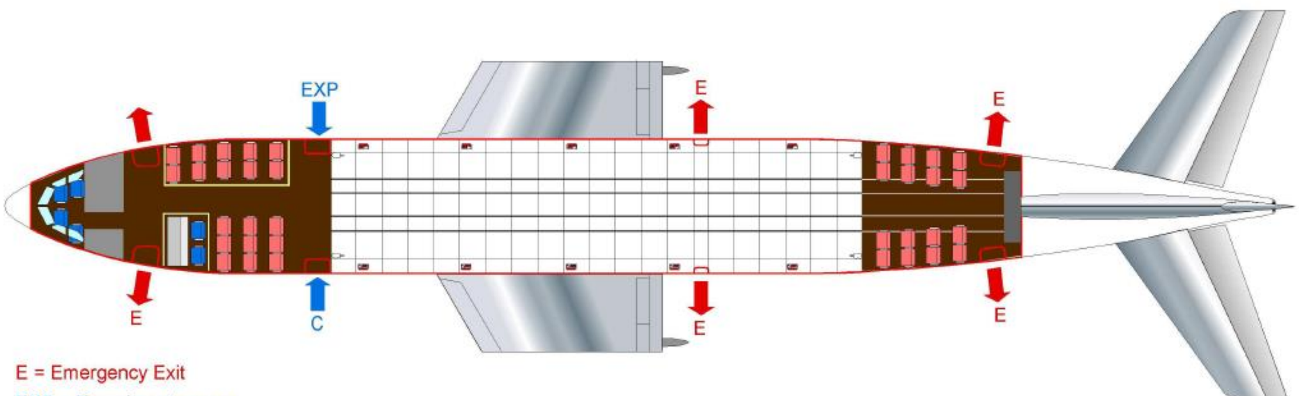


Parabolic flight



Parabolic flight – Airbus A300





E = Emergency Exit
EXP = Experiment access
C = Crew & users access

Parabolic flight - Research

'The vomit comet'

Physicist Professor Stephen Hawking has completed a zero-gravity flight

Fly your Thesis!

ESA education programme

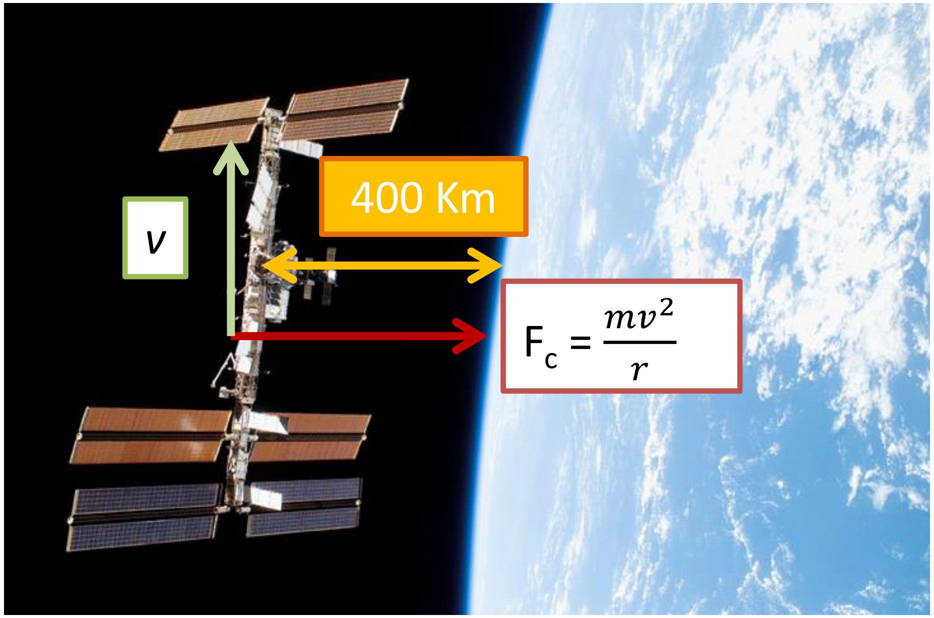
Allows Master and PhD students to design, build and fly scientific or technology-related experiments in microgravity.

Teams wanting to participate in the Fly your Thesis! programme have to propose an experiment as part of their Master's or PhD thesis or research projects that requires microgravity conditions to be performed and that can be run on **parabolic flights.**

International Space Station (ISS)

- Extended periods of microgravity that can reach 10^{-6} g.
- Regular and frequent transport of material to and from the microgravity laboratory facilities.
- Permanent presence of highly trained crew.
- The ability to carry out extended human physiology experiments in microgravity.
- Access to specialized laboratory modules designed to carry out experiments in materials science, fluid science, foam and emulsion science, biology, human physiology and many other areas.

ISS- Free fall

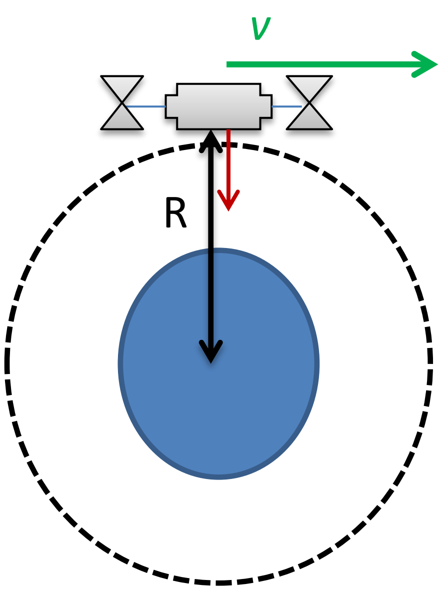


How does the ISS stay in orbit?

In order to stay in a circular orbit at a given distance from the center of Earth, r, the ISS must travel at a precise velocity, *v*.

The orbital velocity!

Orbital velocity



$$F_g = \frac{GMm}{R^2}$$

Force of gravity

$$F_C = \frac{mv^2}{R}$$

Force with centripetal acceleration

$$F_g = F_c$$

$$\frac{GMm}{R^2} = \frac{mv^2}{R}$$

$$v = \sqrt{\frac{GM}{R}}$$

Orbital Velocity

The orbital velocity does not depend on the mass of the space station.

Period

T = Period = time the *ISS* will need to complete one turn around the Earth.

$$v = \sqrt{\frac{GM}{R}}$$

$$v = \frac{d}{t} = \frac{2\pi R}{T}$$

Travelled distance

We can calculate the ISS period and velocity:

v = 27.500 km/h
T = 90 min

$$T = \frac{2\pi R}{v}$$

$$T = \frac{2\pi R^{\frac{3}{2}}}{\sqrt{GM}}$$

Orbital velocity

Kepler's third law

Circular orbit

Relates the orbital period to orbital distance

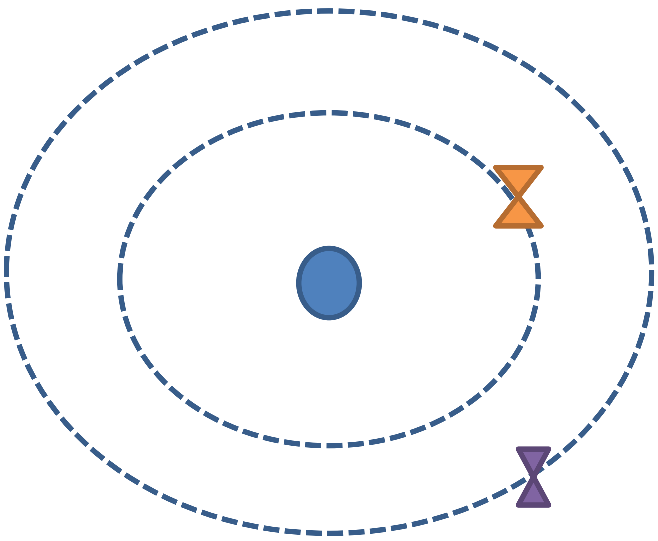
$$T = \frac{2\pi R^{\frac{3}{2}}}{\sqrt{GM}}$$

$$T^2 = \frac{4\pi R^3}{GM}$$

$$\boxed{T^2 = KR^3}$$

K= Kepler's constant

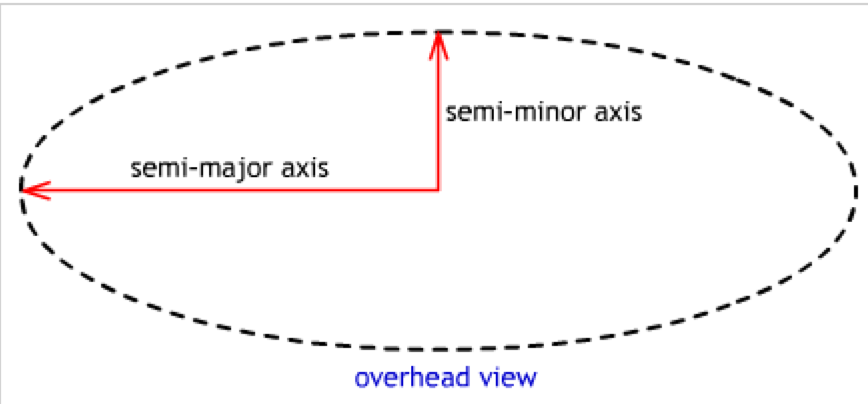
$$\frac{T^2}{R^3} = \frac{T^2}{R^3}$$



Every planet has its own unique K

Kepler's third law

For elliptical orbits



a= Semi-major axis

$$F_g = \frac{GMm}{R^2}$$

$$\mu = GM_{Earth}$$

$$T = 2\pi\sqrt{\frac{a^3}{\mu}}$$

$$\boxed{T^2 = 4\pi^2\frac{a^3}{\mu}}$$

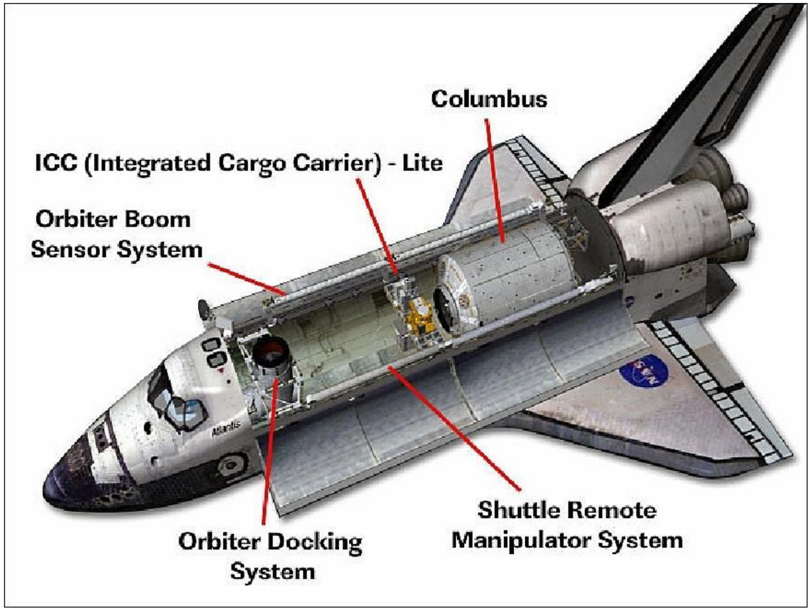
$$\boxed{v(r) = \sqrt{\mu\left(\frac{2}{r} - \frac{1}{a}\right)}}$$

The ***velocity*** of the satellite will be a function of the radius vector from the centre of mass of the Earth.

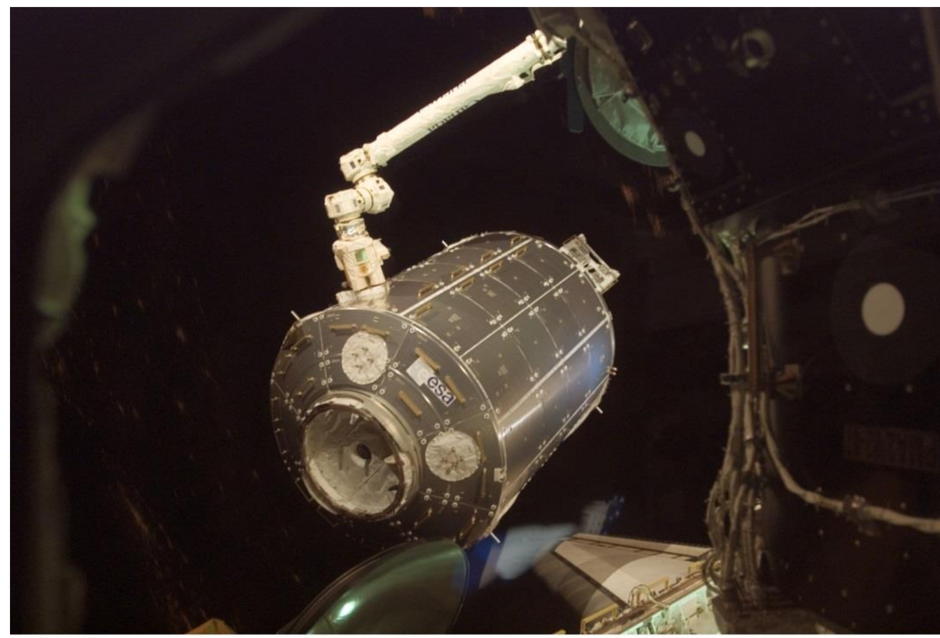
The International Space Station

- The first piece of the International Space Station was launched in 1998. It took 10 years to complete and about 30 launches with different parts transported in the Space Shuttles.
- The most expensive construction ever! (€100 million in 10 years).
- It has a size of a football field and consists of several modules.
- Six crew members live and work there for periods of 3-6 months.
- ESA (European Space Agency) has its own module called COLUMBUS (2008)
- Microgravity research is performed within areas such as physics, biotechnology, biology, human physiology, material sciences etc.

Columbus Installation



On 2008 the European module Columbus was attached to the starboard side of the Node 2 module of ISS.



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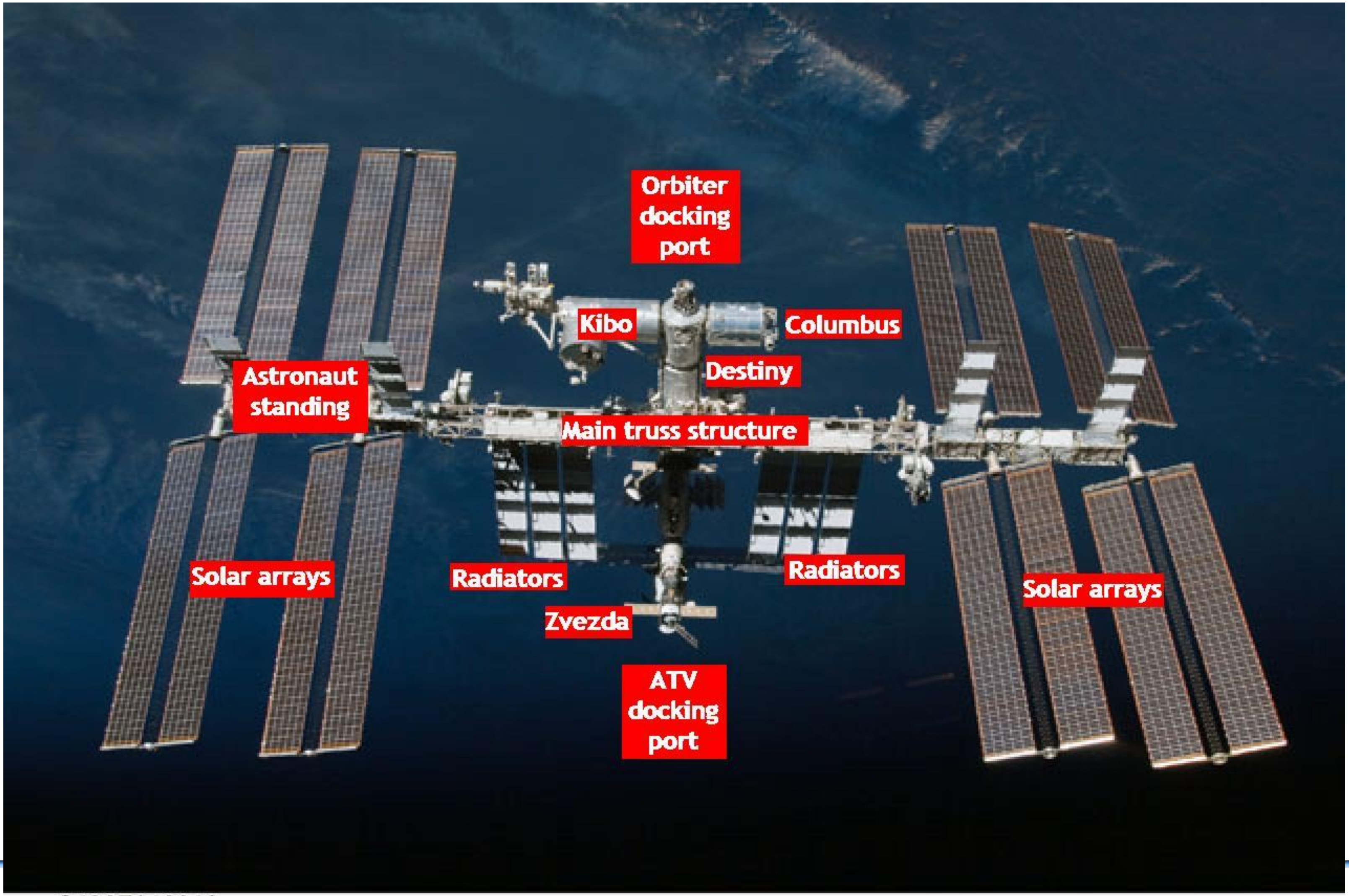
ISS configuration



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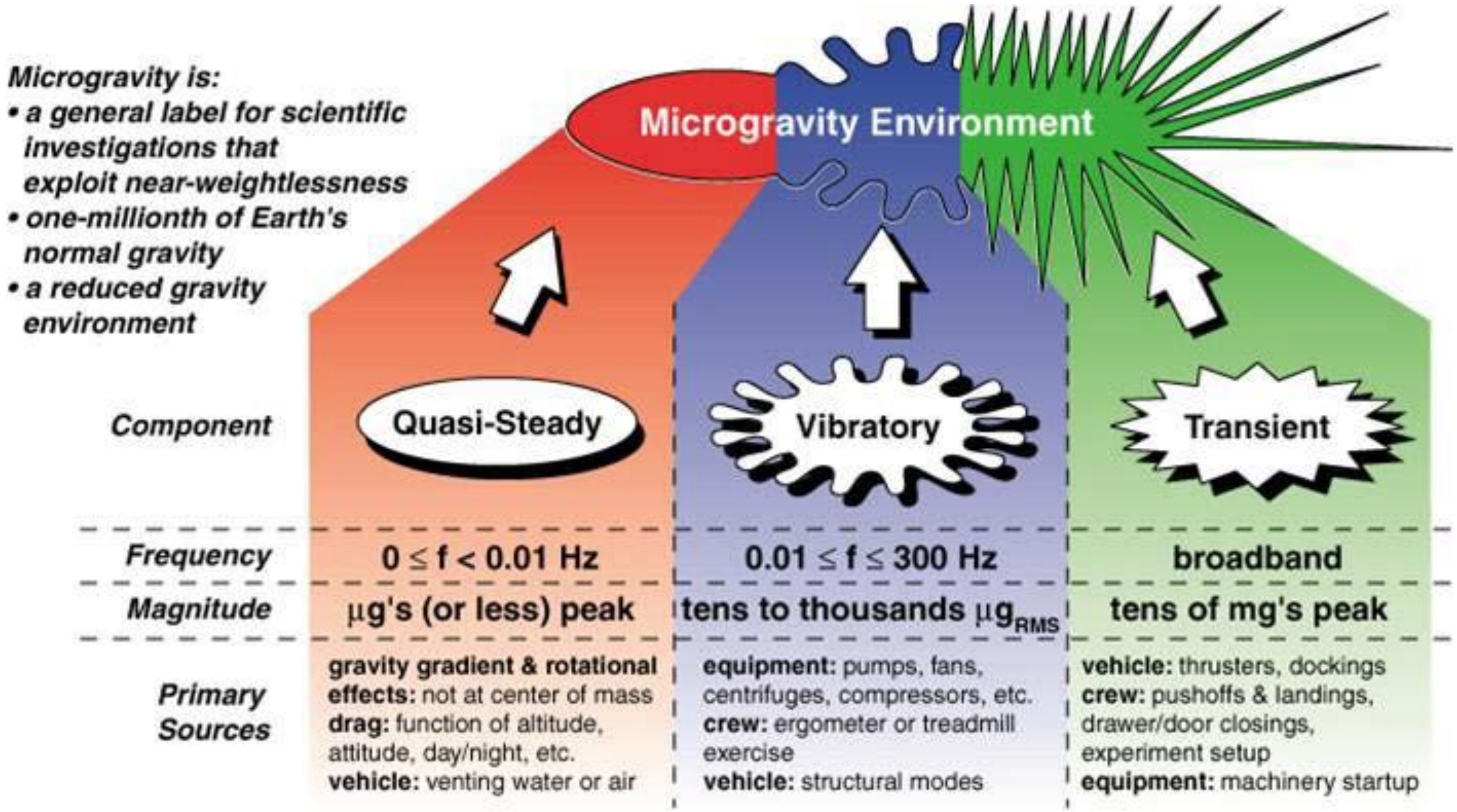
Microgravity environment on the ISS



On-board sensors monitor disturbances to the microgravity state on the ISS.

What changes in microgravity (free fall)?

Phenomena affect by gravity

- Convection
- Sedimentation and buoyancy
- Capillary forces
- Surface tension
- Pressure
- Fire phenomena

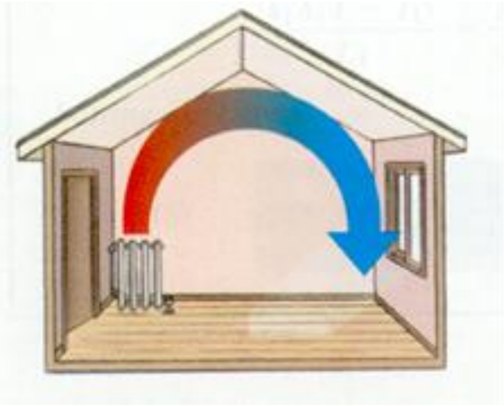
Buoyant forces

Natural convection is a mechanism, or type of heat transport in which the fluid motion is not generated by any external source (like a pump, fan, suction device, etc.) but only by density differences in the fluid occurring due to temperature gradients.

The driving force for natural convection is buoyancy, a result of differences in fluid density.

$$B = \rho_f V g$$

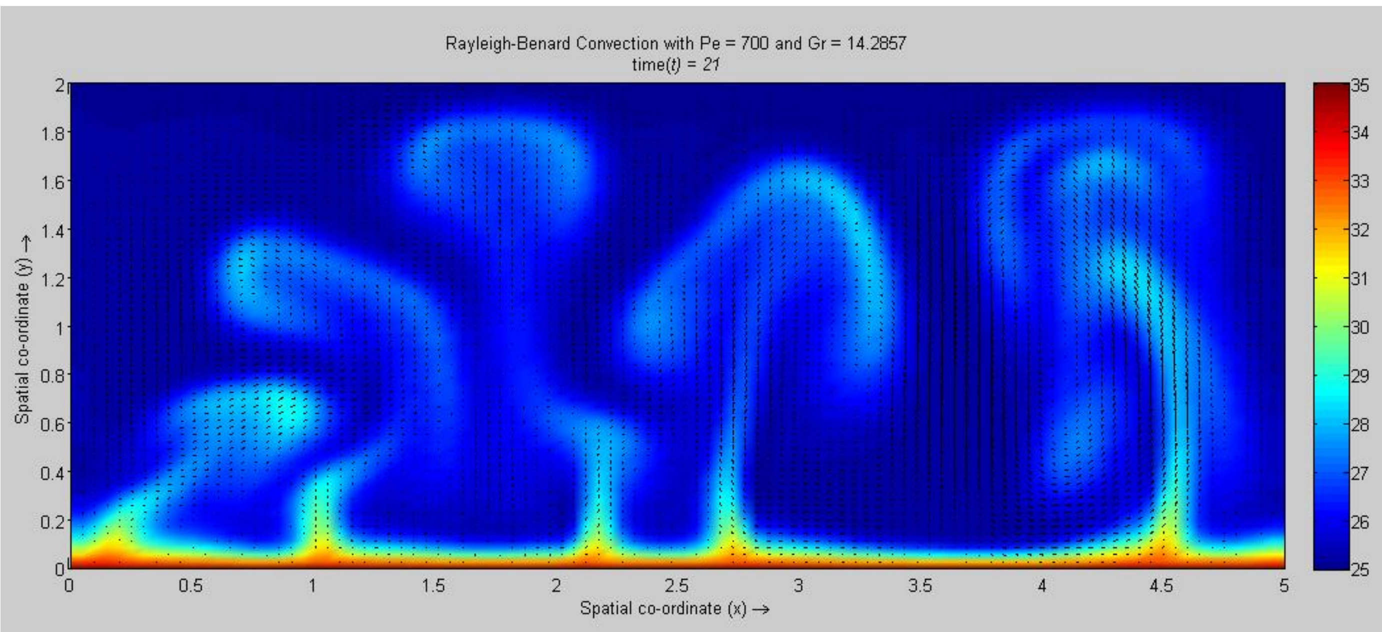
ρ = fluid density
V= Volume of displaced fluid
g= gravity



Thermal convection

Thermal convection, also called Rayleigh-Bénard convection, <u>is the transfer of heat through fluid motion.</u>

Rayleigh number



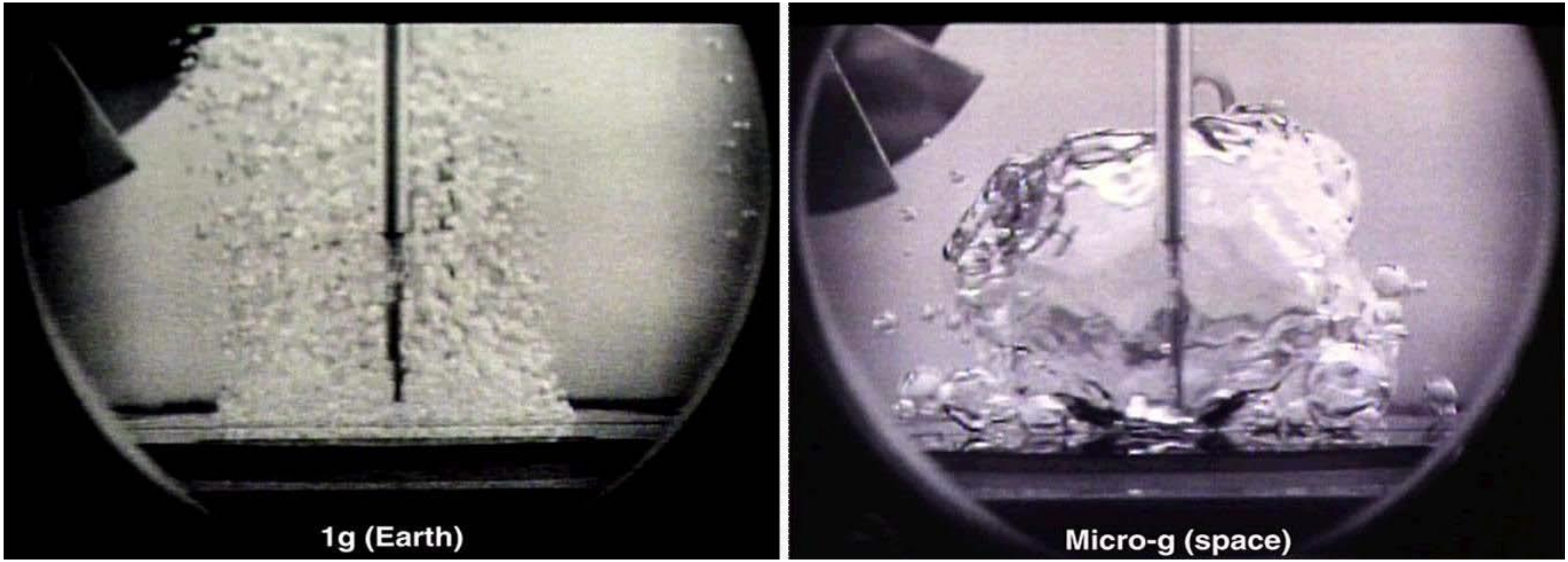
$$\mathrm{Ra}_L = \frac{g\beta}{\nu\alpha}(T_b - T_u)L^3$$

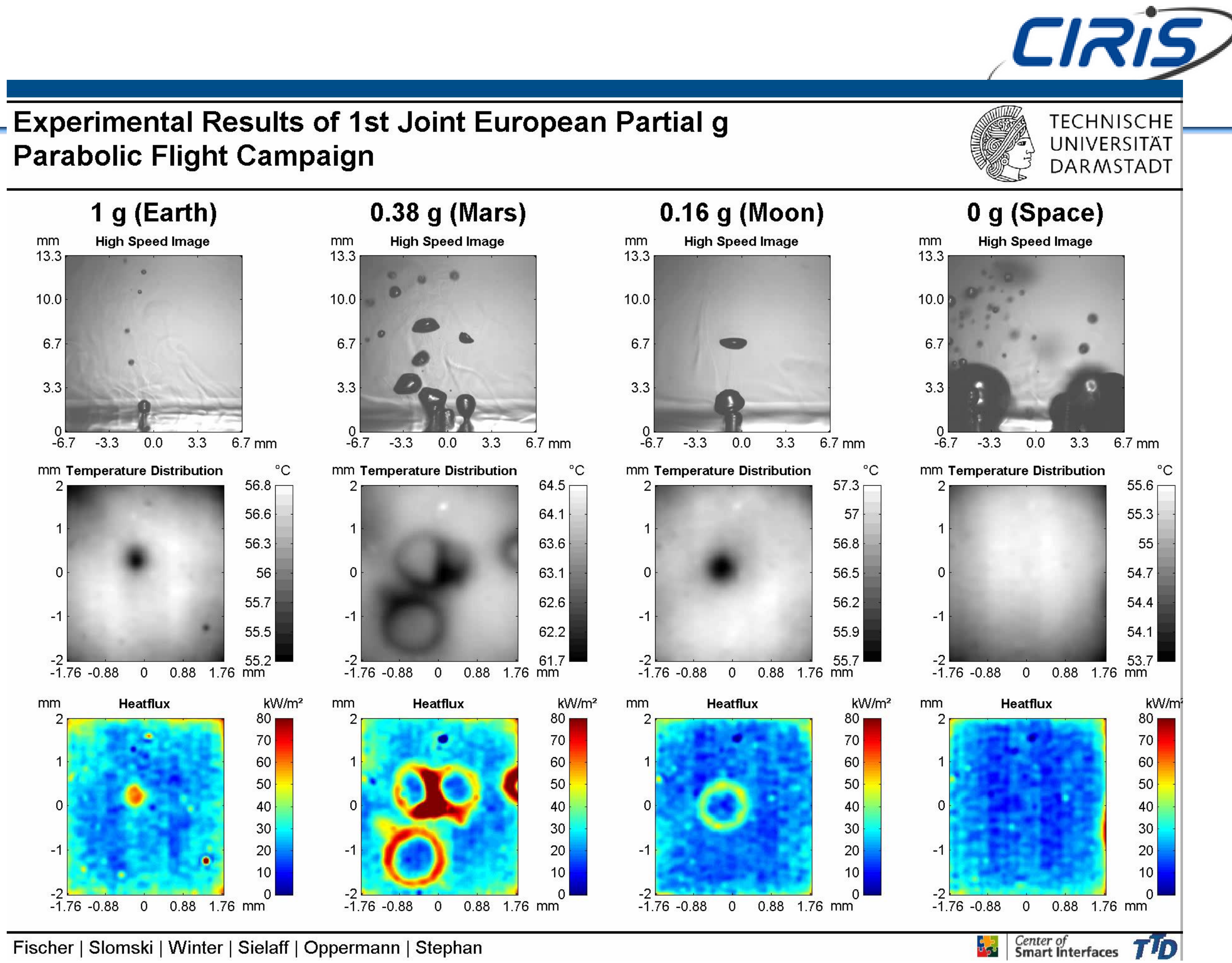
T_u is the temperature of the top plate
T_b is the temperature of the bottom plate
L is the height of the container
g is the acceleration due to gravity
ν is the kinematic viscosity
α is the Thermal diffusivity
β is the Thermal expansion coefficient.

Rayleigh-Bénard convection occurs in a plane horizontal layer of fluid heated from below, in which the fluid develops a regular pattern of convection cells known as **Bénard cells**

Thermal convection

Water boiling in microgravity

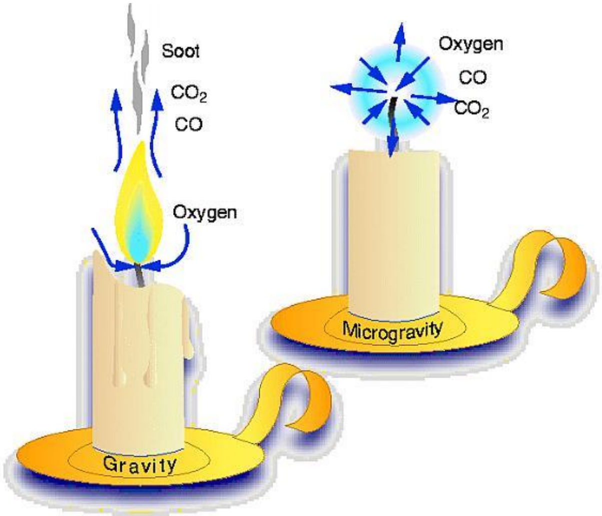




Nucleate boiling – bubbles growing in a heated surface and how it evaporates

Flame - absence of gravity (free fall)

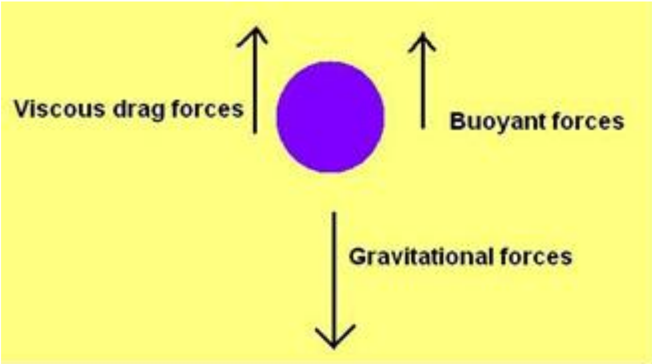
On Earth the hot, expanding gases in flames are forced to rise by cooler, denser gases in the surrounding air which displace them. In orbit, however, a space vehicle and its contents experience almost no gravitational forces so convection currents cannot flow and the hot expanding gases can become spherical.

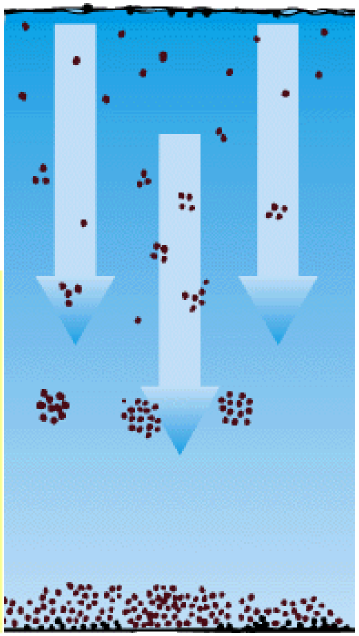


Sedimentation

Sedimentation describes the motion of molecules in solutions or particles in suspensions in response to an external force such as gravity, centrifugal force or electric force.

$F_{(grav)} - F_{(buoy)} - F_{(drag)} = 0$





1g - on Earth

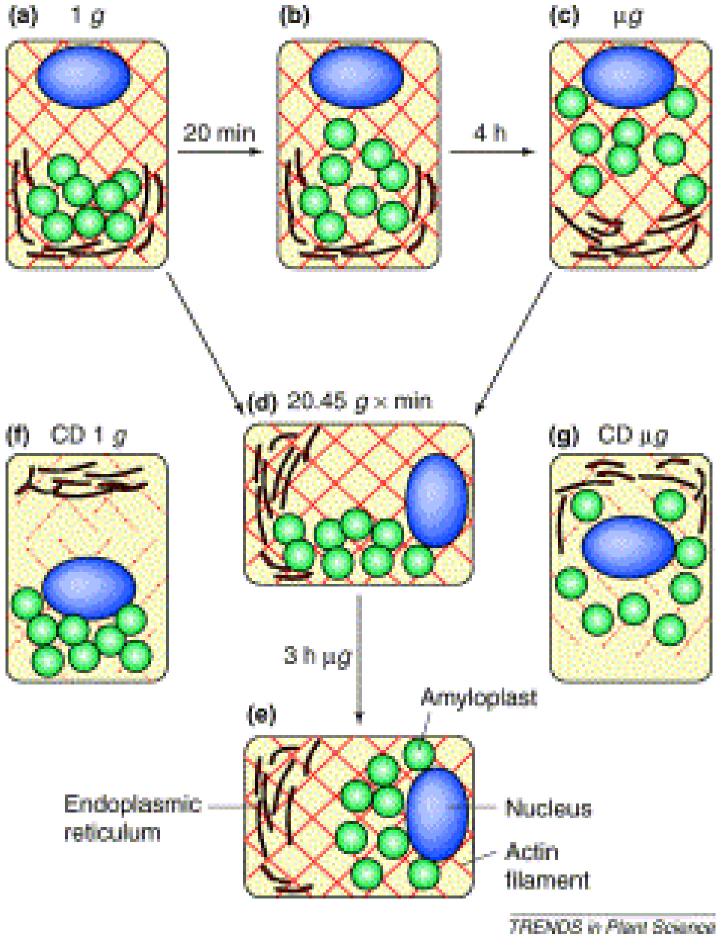
Sedimentation disappears in microgravity

Terminal velocity of the moving sphere though the liquid

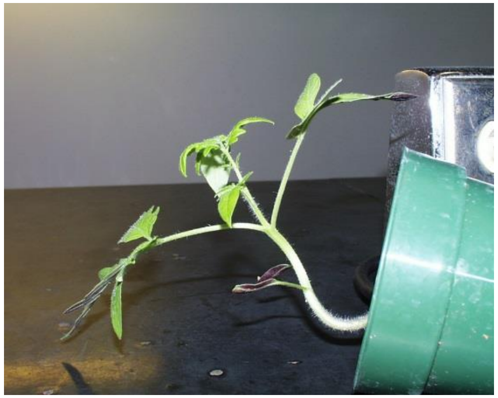
$$v_T = \frac{2r^2(\rho_p - \rho_s)g}{9\eta}$$

ρ_p = density of ball
ρ_s= density of the fluid
η= fluid viscosity
r= ball radius

Plants sensing gravity



g



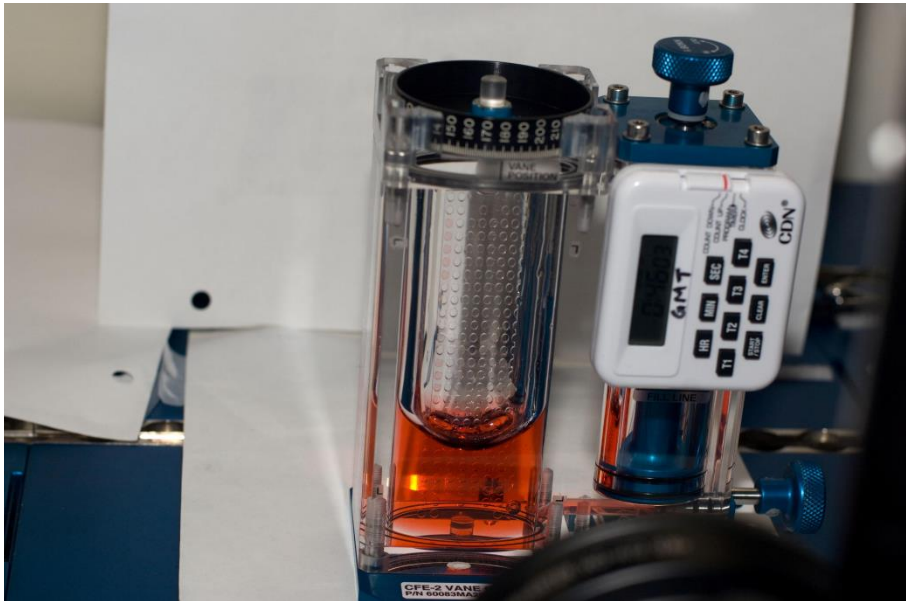
Plants use the sedimentation of the amyloplasts to sense gravity. In microgravity there is no sedimentation. Plants cannot use gravity to find the growth direction to shoots and roots.

Capillary Action

$$h = \frac{2\gamma cos\theta}{\rho g r}$$

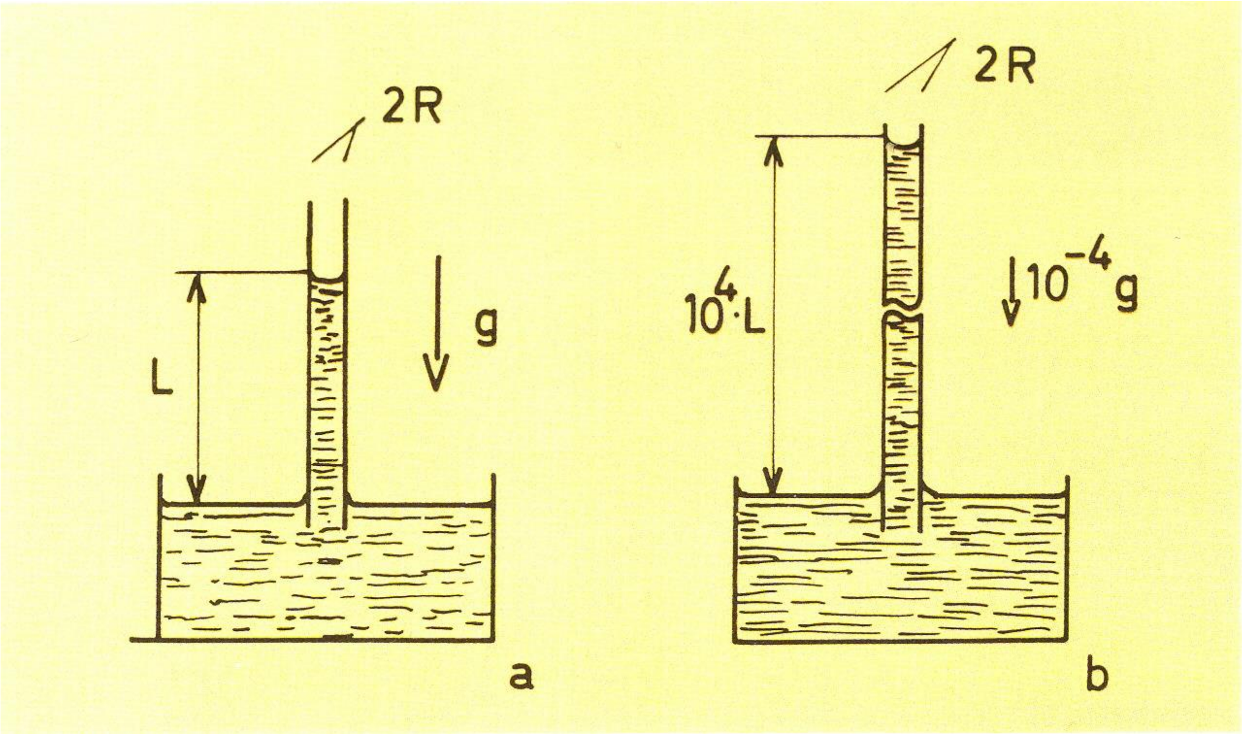
The capillary effect is *enhanced* in microgravity

γ is the liquid-air surface tension
ρ is the density of the liquid
r is the radius of the capillary
g is the acceleration due to gravity
ϑ is the angle of contact
h is the height the liquid is lifted



*NASA - **Capillary Flow Experiment (CFE)***

Capillary forces in microgravity



The same capillary (diameter 2R) is used in the experiment in the figure above. Since the *g*-value is 10,000 times lower, the capillary forces will raise the liquid 10,000 times higher.

Fluid Dynamics

- Fluid dynamics is challenging in microgravity

Difficult to control the flow (challenge: liquid propellants, thermal control, and waste-water management).

- Capillary forces can be used to control fluid orientation on spacecraft

Important to create more predicable systems.

Capillary Beverage

NASA experiment: *Capillary Effects of Drinking in the Microgravity Environment*

- studies the process of drinking from specially designed ***Space Cups*** that use fluid dynamics to mimic the effect of gravity.
- To demonstrate earth-like drinking from a cup that exploits capillary forces rather than gravitational forces during the casual consumption of a variety of onboard drinks

The zero gravity cup

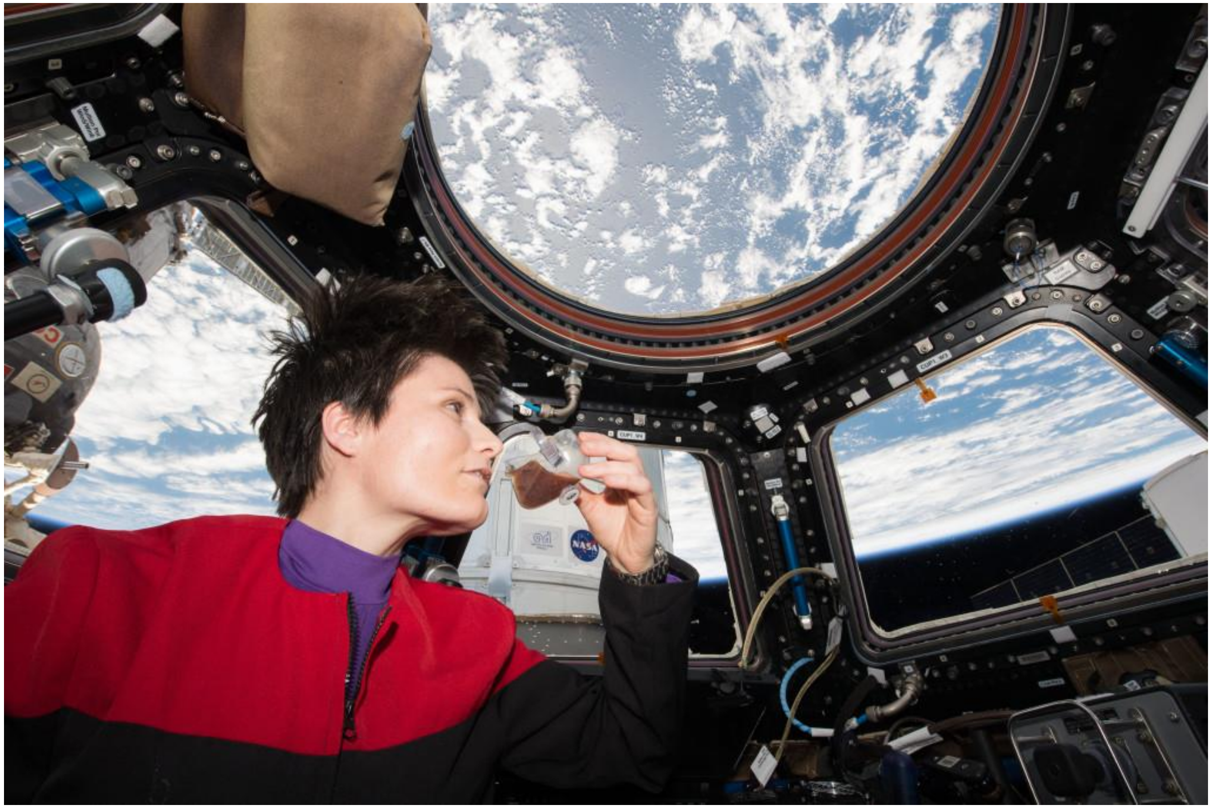
Space Station Live: ISS

Space Cup Full of Science

Interview with ***Mark Weislogel***, Principal Investigator of the Capillary Beverage Experiment

https://www.youtube.com/watch?v=0Lmsvr8VVwM

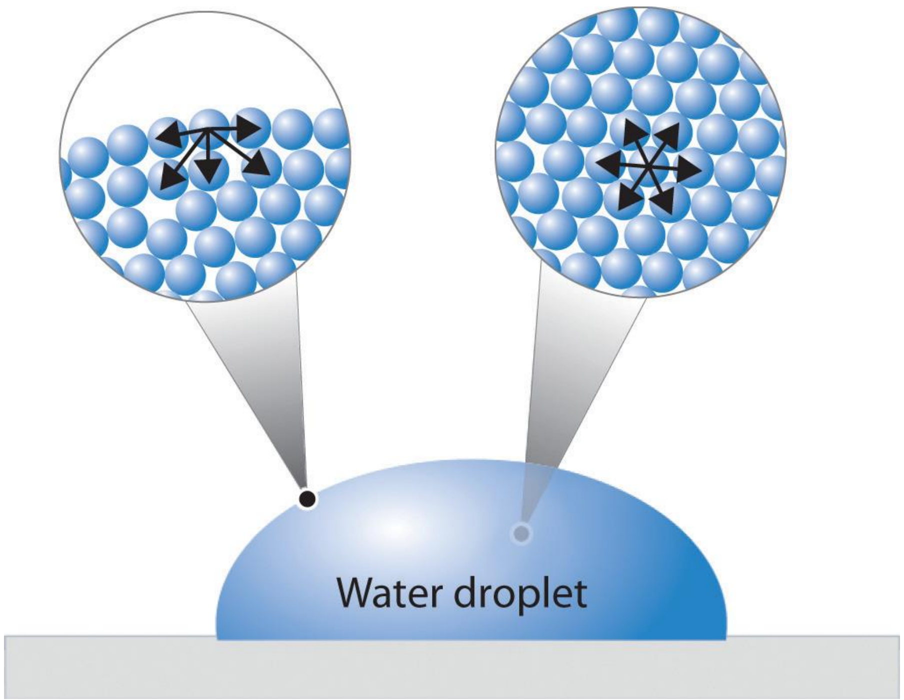
Capillary Beverage



European Space Agency (ESA) astronaut Samantha Cristoforetti – dressed in a Star Trek Voyager uniform – takes a sip of espresso from the new Capillary Beverage experiment

Surface tension

On microgravity the buoyancy-driven fluid flows and sedimentation is greatly reduced. Surface tension becomes more dominant.



Surface tension – 1 g

Water Bubble in Space

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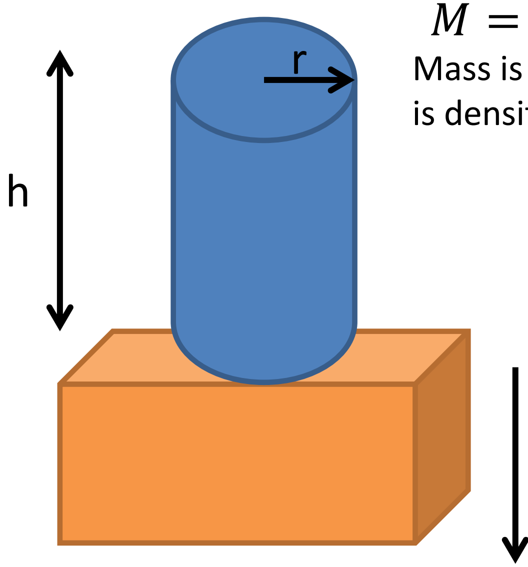
Surface Tension

Does water squezee out of a cloth at Zero Gravity?

https://www.youtube.com/watch?v=Ff7oUycGJRY

Pressure

Pressure is the amount of force acting per unit area.
Pressure is dependent on gravity.



$$M = \rho h \pi r^2$$

Mass is calculated where ρ is density of the cylinder

$$F = Mg$$

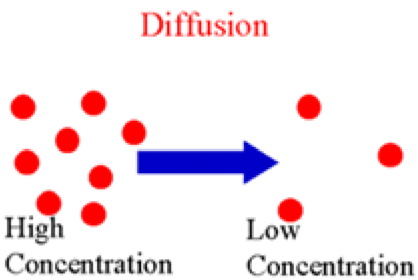
Pressure: force divided by area

$$P = \frac{F}{A}$$

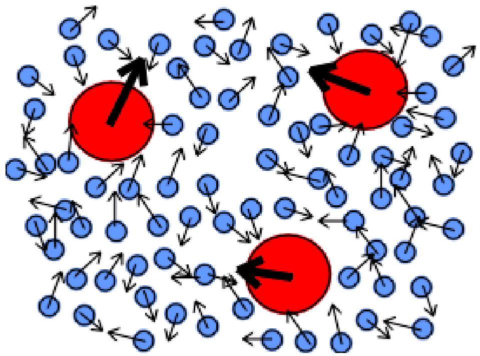
$$P = \frac{Mg}{\pi r^2}$$

$$\boxed{P = \rho h g}$$

Diffusion



$$\frac{dc}{dt} = D\frac{d^2c}{dx^2}$$



Brownian motion of molecules

In order to get exact measurements, the transport must be a result of diffusion only, and not be disturbed by some kind of convection in the liquid.
In microgravity more accurate values of diffusion constants can be measured.

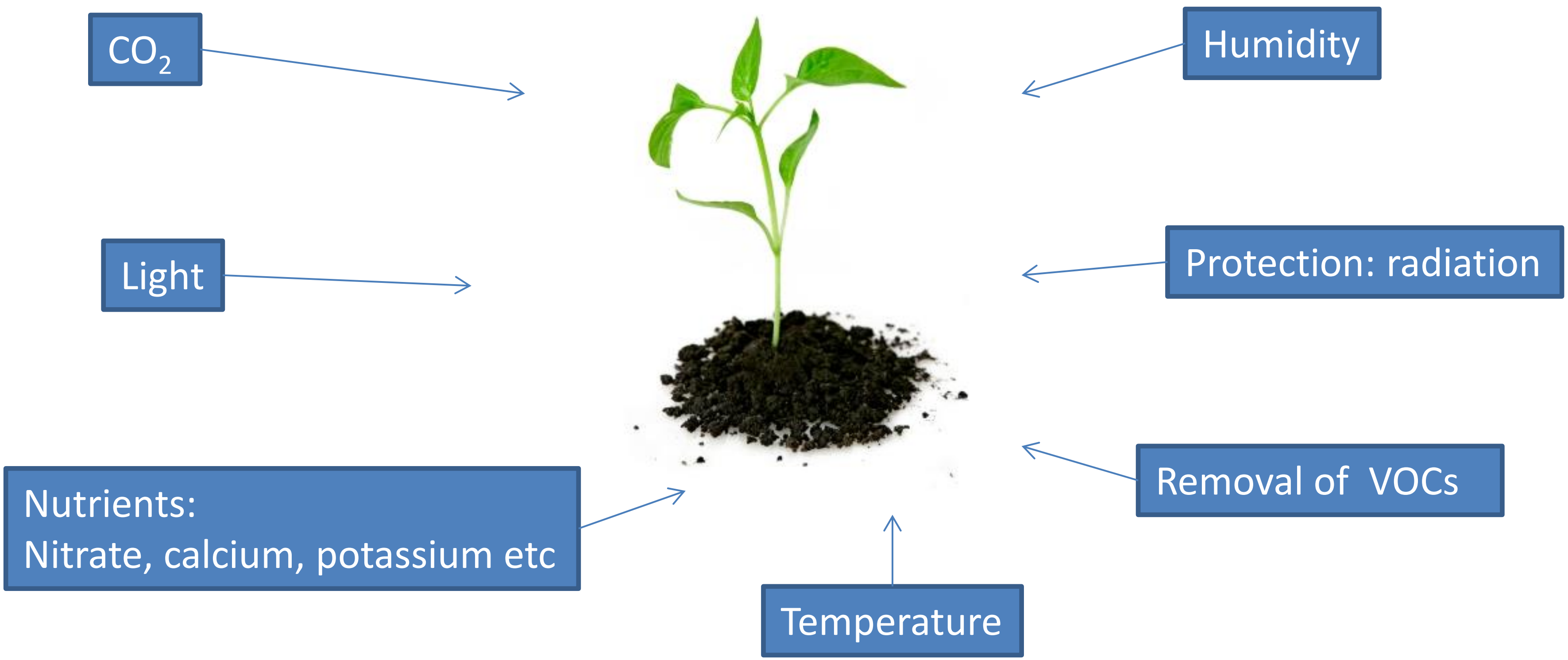
Plants in Space

On the Earth plants are known to adapt to extreme environments, and space experiments have demonstrated that plants are able to grow and reproduce in microgravity.

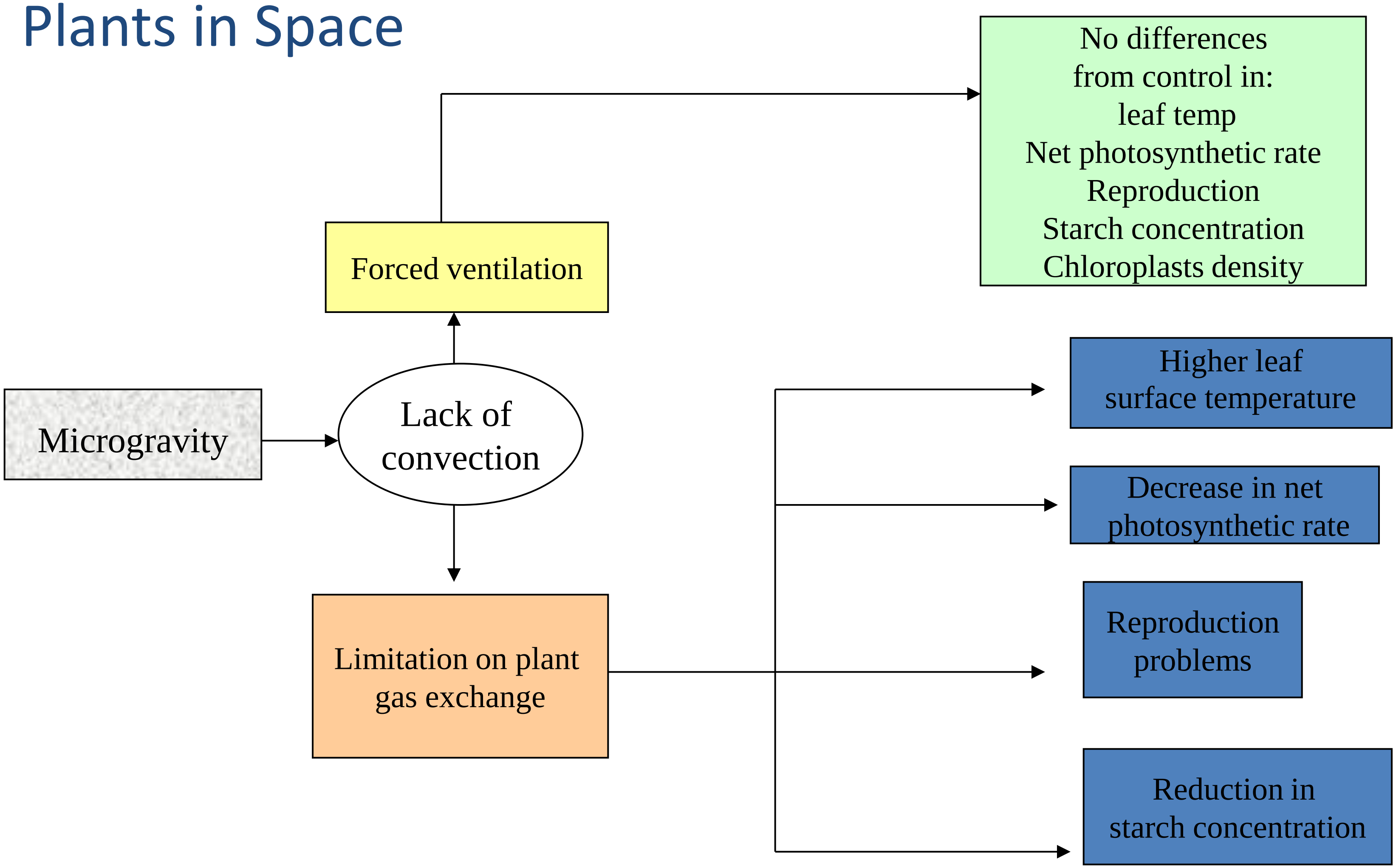
Challenges:

- Long term experiments
- Radiation
- Technological aspects of the Cultivation System

Plants in enclosed environment



Plants in Space

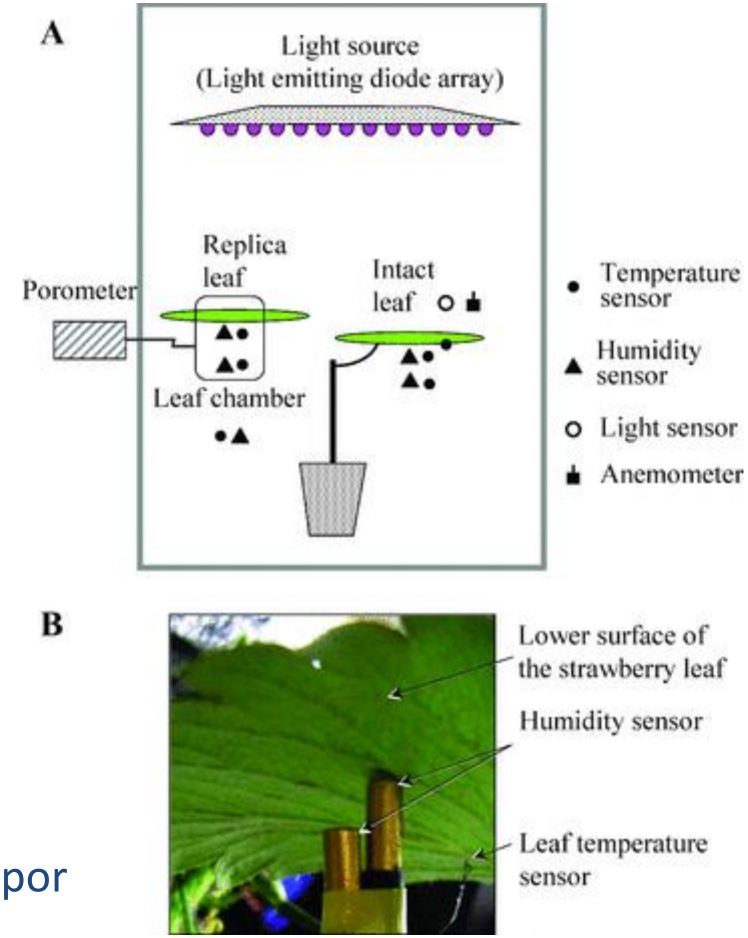


From Research performed in Space

Parabolic flight experiments

The transpiration rate of the intact leaf decreased by 46% with decreasing gravity levels from 1.0 to 0.01 *g* and increased by 32% with increasing gravity levels from 1.0 to 2.0 *g*.

Transpiration rate of leaves was suppressed by retarding the water vapor transfer due to **restricted free air convection** under microgravity conditions



Experimental setup for evaluating water vapor exchange of leaves . *Hirai and Kitaya 2009*

Multigen Experiment

NTNU, Prototech, N-USOC

- Performed in 2007 on the ISS
- Principal Investigators from NTNU Professor:

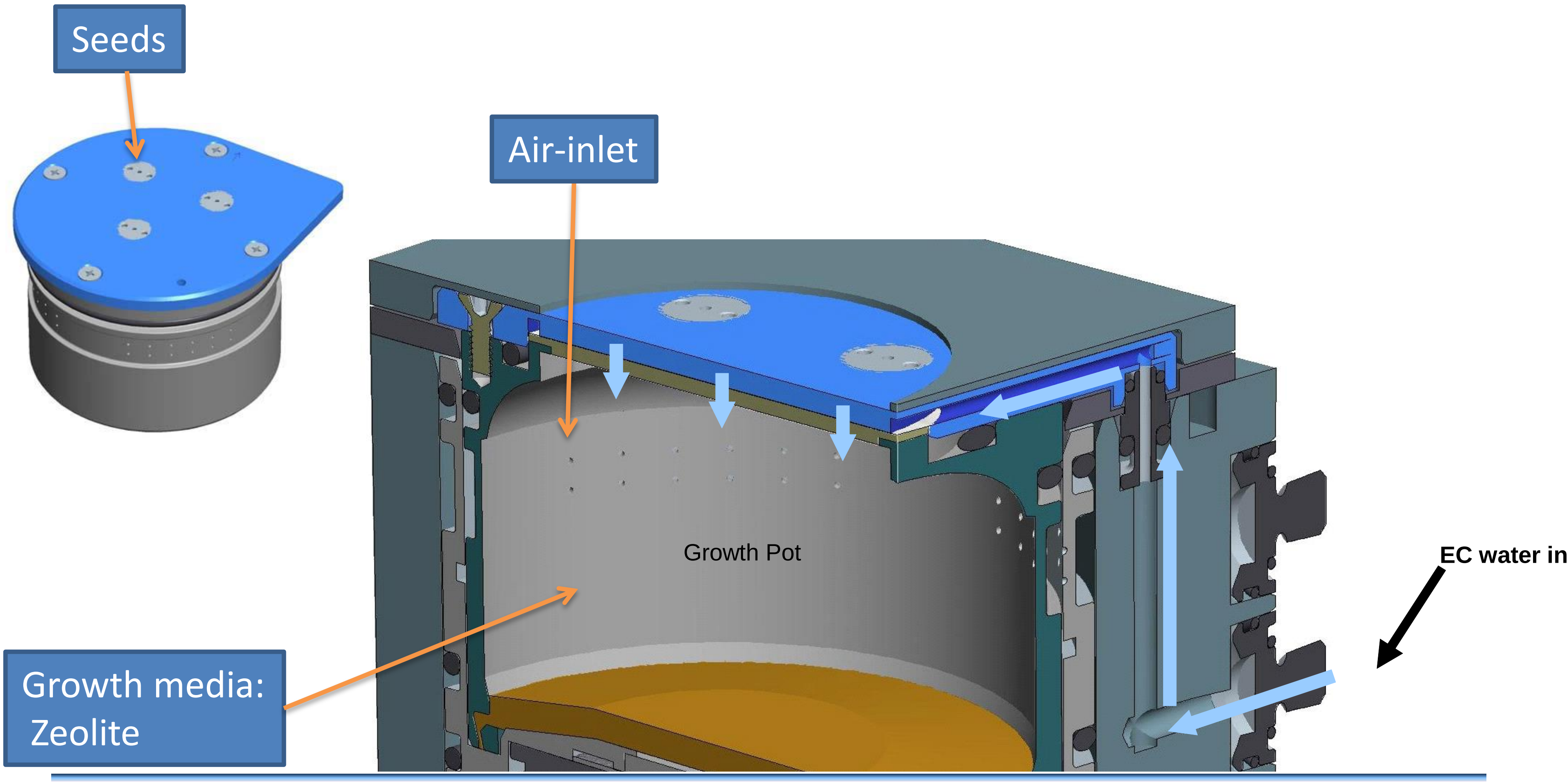
Thor-Henning Iversen and Anders Johnsson

- Prototech from Bergen, build the equipment
- N-USOC supported the test campaign and performed the Real Time operation
- Long term experiment – 84 days

RAMBO-Plant

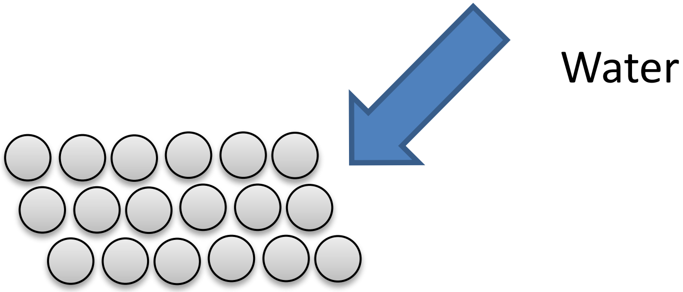
Arabidopsis plant grown in space for 84 days –
The only survivor from the Multigen-1 experiment

Multigen - **Plant Chamber**



Growth media

Zeolite is a type of porous media used in plant space experiment as the root substrate. The idea is that the water will be distributed through capillary forces and surface tension.



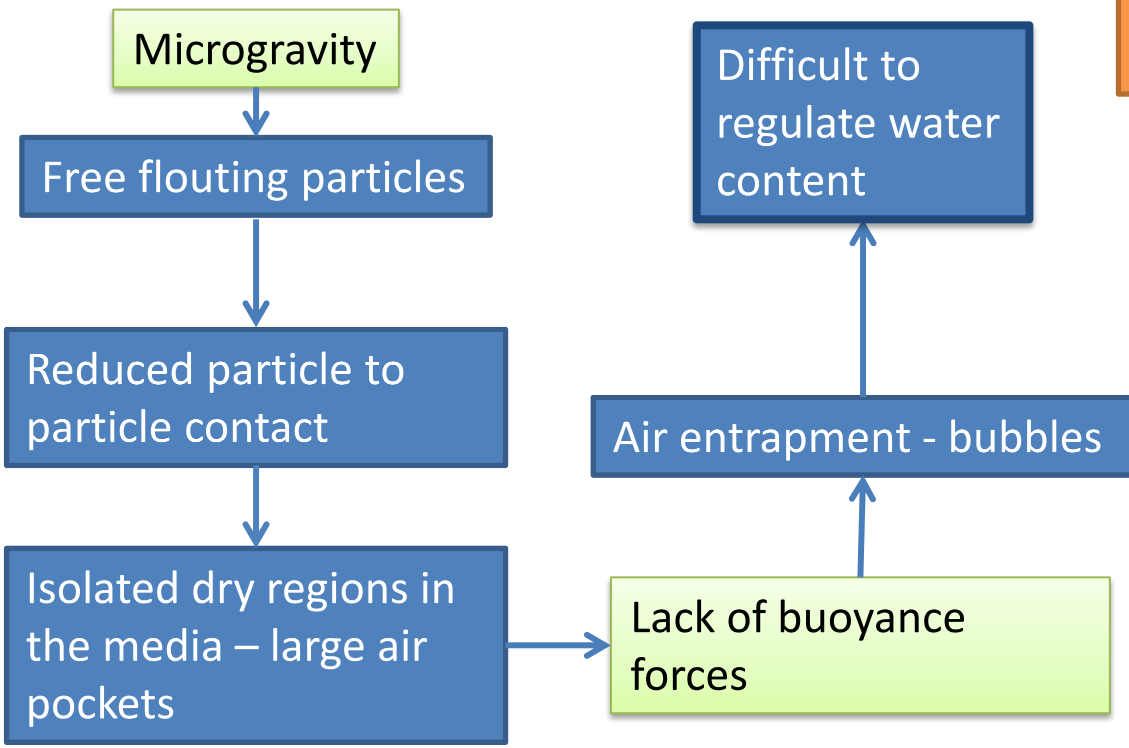
Zeolite

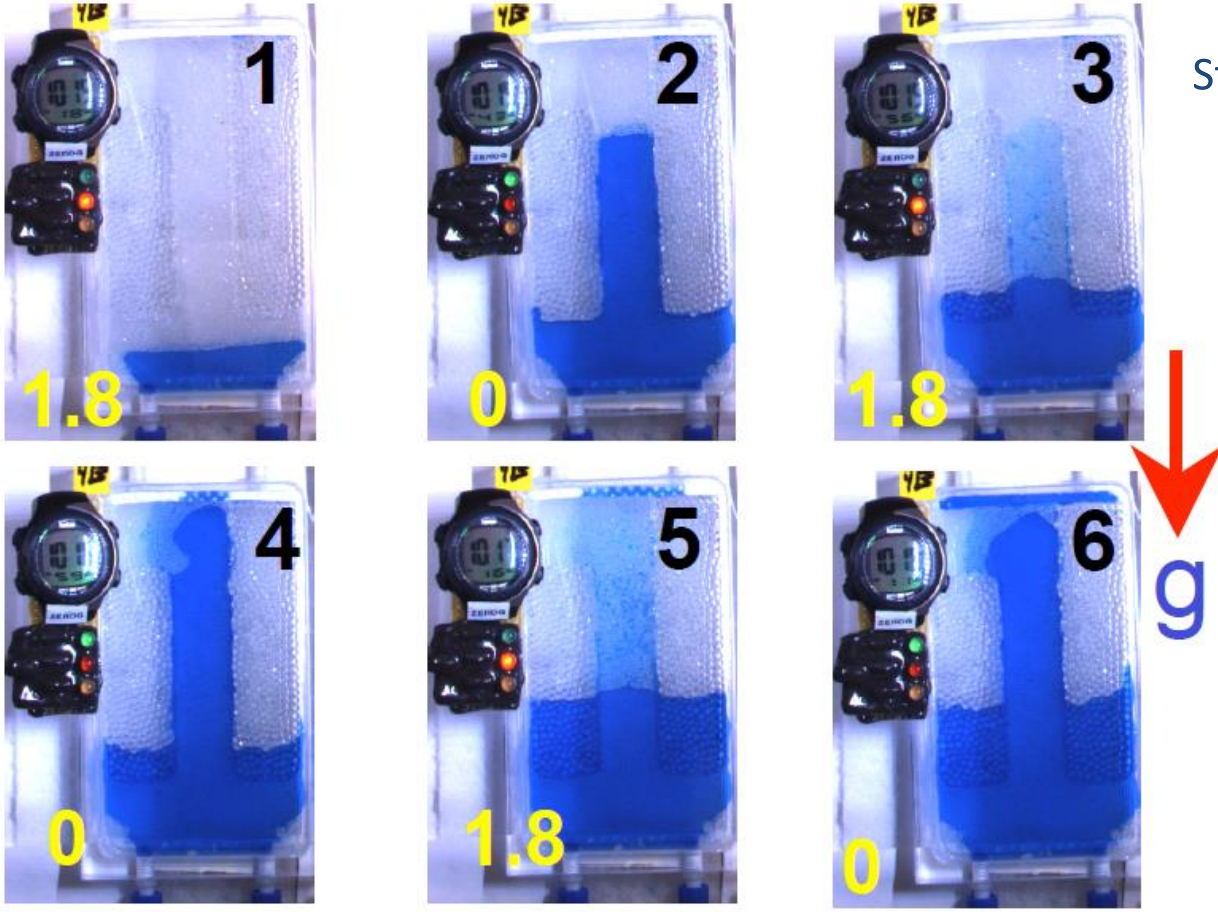
Challenges in microgravity:

- Air entrapment may interfere with water retention
- Rearrangement of loosely packed particles can modify pre-defined transport patter
- Roots

Hydrodynamic aspects

In addition: the plant roots will also disturb the hydrodynamic aspects of the media





Steinberg *et al* 2005

Parabolic flight experiment

Preferential infiltration of water (blue) into finer (0.9 mm) glass beads bypassing coarse regions (2.4 mm). Infiltration proceeds at a faster rate in pre-wetted beads

American Astronaut Scott Kelly and Russian Cosmonaut Mikhail Kornienko have spent one year on the ISS to increase the knowledge on the medical, psychological and biomedical challenges faced by astronauts during long-duration spaceflight

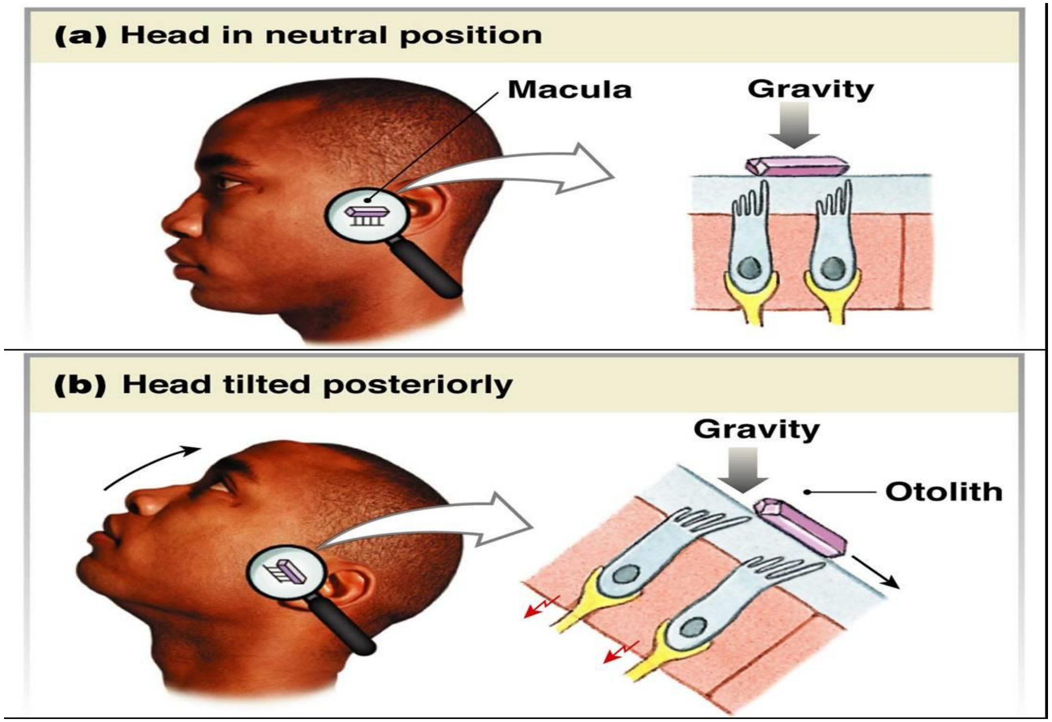
NASA one-year mission

https://www.youtube.com/watch?v=354nLC3r6WA

Microgravity effects in Humans

The vestibular organ act also as a position detecting organ. This organ can sense direction and size of the gravitational force.

The movement or ***sedimentation*** *of a particle in a organ is the key process of the mass perception in the balance system.*



Dysfunctions of the vestibular system are common during and immediately after spaceflight, such as space motion sickness in orbit and balance disorders after return to Earth.

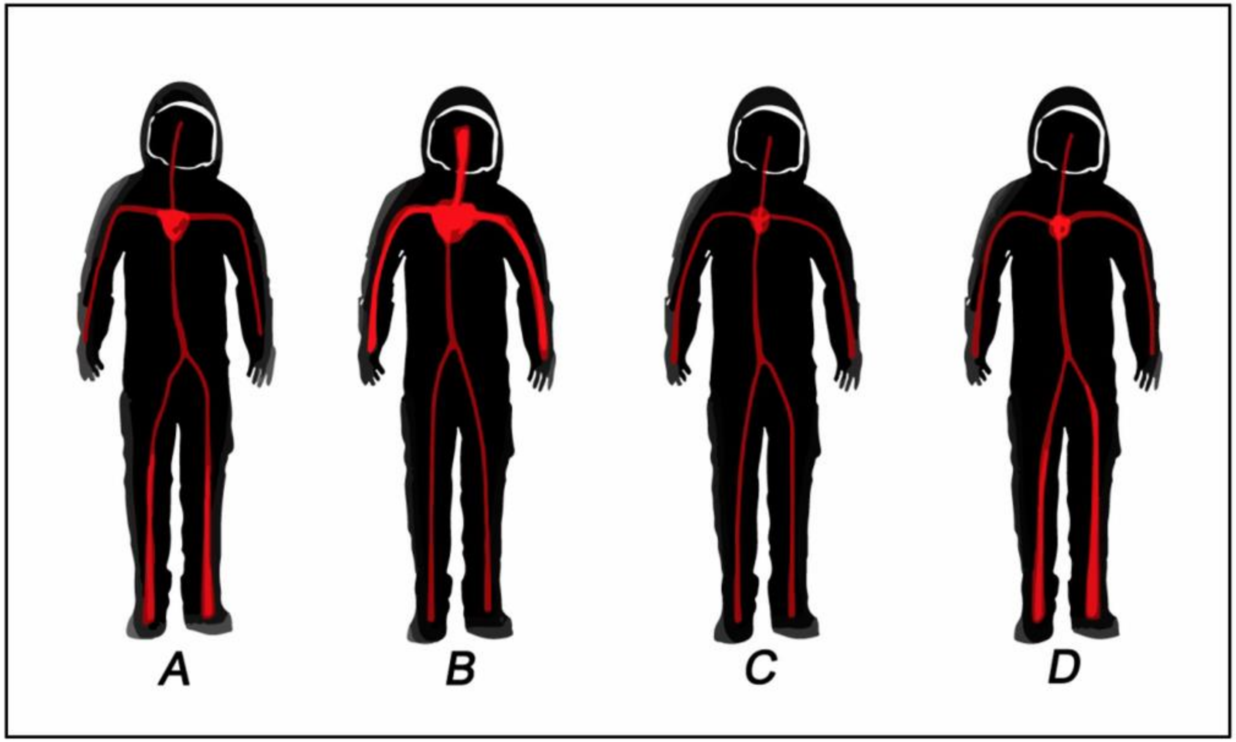
NEUROSPAT

ESA experiment

Neurospat records an astronaut's brain activity while looking through virtual-reality goggles to detect differences in how the brain interprets spatial cues on Earth and in space.

The experiment in Europe's Columbus laboratory required carefully positioning 62 electrodes on the astronaut's head

Blood circulation



The effect of space on blood circulation. (**A**) Normal gravity (Earth); (**B**) acute zero-microgravity exposure (first day in space); (**C**) prolonged zero-microgravity exposure; (**D**) upon return to Earth. ***Torre 2014 Life***

Bone loss in space

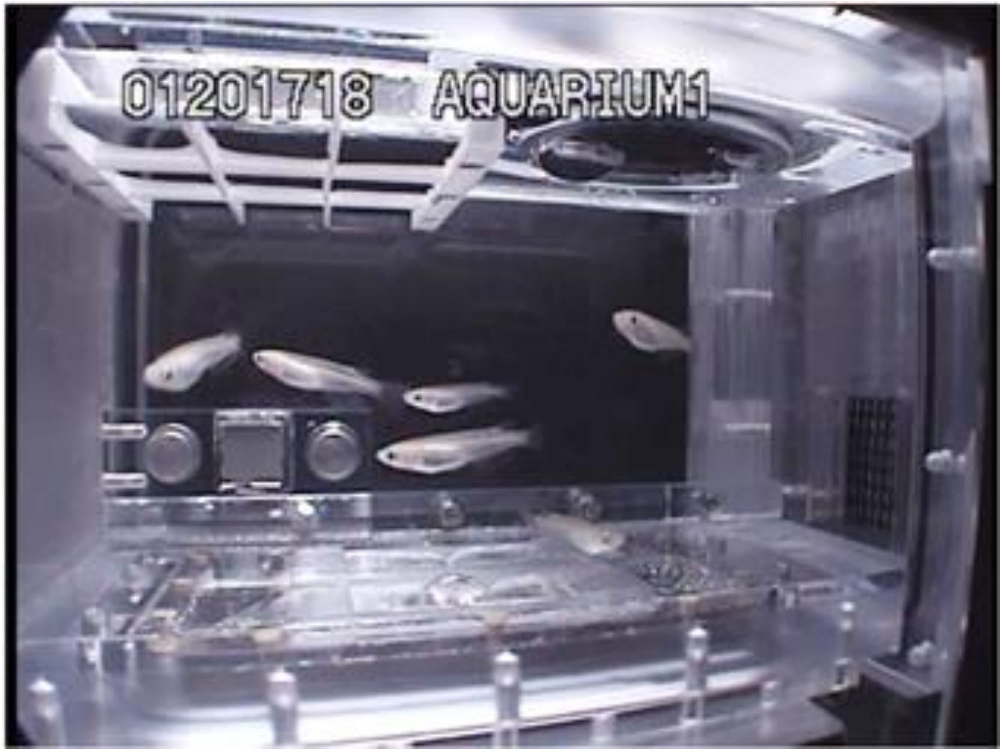
The bone mineral density (BMD) of astronauts decreases specifically in the load-bearing bones during spaceflight

The calcium balance (the difference between intake and excretion), which is about zero on Earth, decreases to about -250 mg/day during flight, a value that increases the risk of kidney stones.

Men and Women in Space: no difference in the rate of bone loss
Smith et al 2014 Journal of Bone and Mineral Research

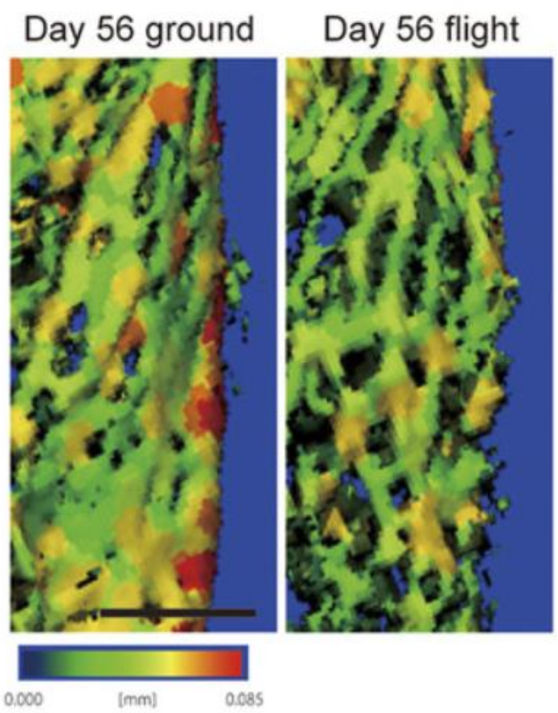
Bone loss experiment on the ISS

Medaka Osteoclast II: Japanese experiment that studied the effects of microgravity on the osteoclast activity and the gravity sensing system of the vertebulate using Medaka fish on board the Kibo Module.

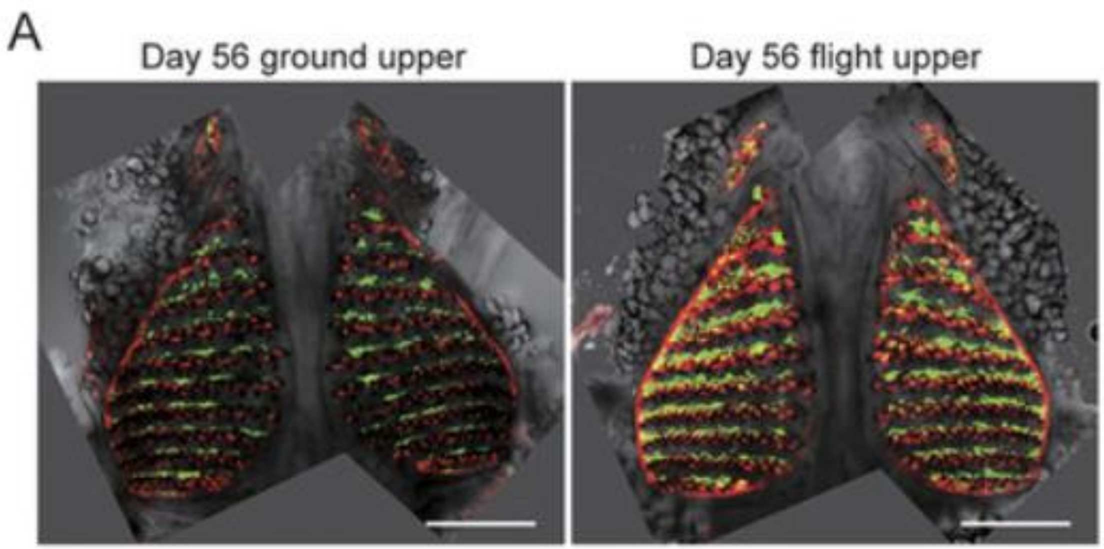


Medaka «fishonauts»

Results from Mekada fish experiment



Mineralization status of the pharyngeal bone at day 56 showed thinner bone for the flight fish



Fluorescence imaging of pharyngeal bone shows enlargement of osteoclasts in the flight medaka at day 56

Chatani et al 2015, Nature

Exercise

Astronauts have to work out 2 hours every day to minimize muscle atrophy

Summary (1)

How to perform Microgravity Research?

- ✓ Drop tower – 4/9 seconds
- ✓ Parabolic Flight – 20 seconds
- ✓ ISS long term microgravity environment

What changes in microgravity?

- ✓ Buoyancy Forces, sedimentation, thermal convection, pressure are absent in microgravity
- ✓ Capillary forces are enhanced
- ✓ Surface tension, diffusion are more dominant due to the lack of the gravity dependent forces

Summary (2)

- Plants have showed to grow and reproduce in space
- Lack of gravity (buoyancy forces) will affect transpiration, gas exchange and photosynthesis: forced ventilation is necessary
- Technological aspects of the plant chamber is important to fulfil all of a plant’s requirements (water, nutrients, light, CO_2)
- Long term experiments need to be performed
- Experiment with crop plants need to performed

Summary (3)

The human body (internal cellular process) will be affected by the lack of gravity

- ✓ Bone loss
- ✓ Muscle loss
- ✓ potential errors in perception: spatial orientation and mental representation