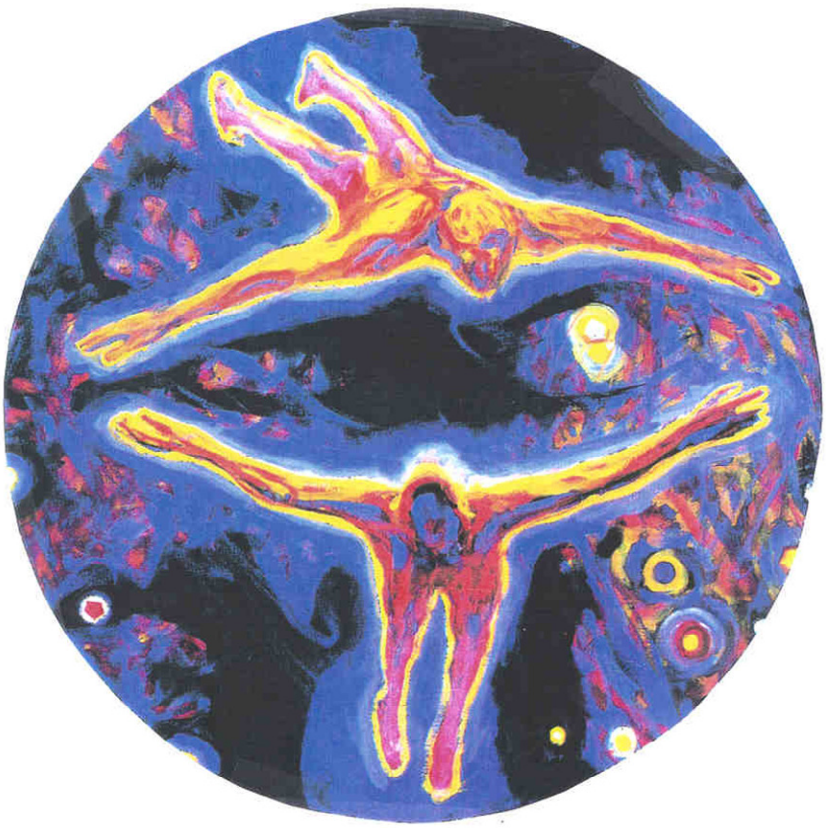
MICROGRAVITY

TTT 4234 SPACE TECHNOLOGY I



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SPACE TECHNOLOGY

MICROGRAVITY

The present notes are used in different course contexts and the level of the presentation is, therefore, identified out from different requirements. For students from the physics disciplines some parts will turn out to be at a fairly introductory level, for students from biological disciplines the same parts might be at a more advanced level.

Chapter 1 is such a chapter. It introduces and discusses the concept of Gravity and the Law of Gravity and the physics students should have digested it before entering a course in Space Technology. However, out from teaching experience, I would like the physics students to contemplate the concept of *weightlessness* once more. It is fundamental for the understanding of space technology and the student should be able to understand why a space vehicle in orbit around the Earth is in weightlessness, although the gravitational acceleration is only slightly smaller than at the Earth surface.

The term *microgravity* has been adapted in the notes, simply meaning the presence of a small gravitational force, and often used as a synonym to weightlessness. The term *free fall* is, however, frequently used and describes the *weightlessness* conditions in an illustrative way.

The notes try to give a short overview of experimental areas of interest to explore in weightlessness. Also some experimental phenomena and experimental set-ups that are of interest in space technology will be discussed.

The notes are not complete. Misprinting, mistakes and non-corrected texts can hopefully be corrected and the author is thankful for any comments helping to improve the quality of the present edition.

Trondheim, September 2015

A. J.

1. THE LAW OF GRAVITY, FREE FALL.

1.1 A life with gravity.

Based on paleontological findings of cell like structures, the experts claim that life, in the sense we understand it, dates back some billion years, approximately 3,5 billion years. The exact age, which is also dependent on how we define the origin of life, is still not precisely known, but we can state that the *force of gravity* has constantly been present in this period.

No organism has been able to avoid the force that pulls us towards the centre of the earth. The evolution has taken place in the presence of this force, and it will therefore be important to view the development of the different forms of lives against the background of gravity. This force has affected our surroundings, our development, and the shape and physiology of our own bodies. The development of man during the last hundred thousand years is no exception from this process. Physical processes clearly influenced by gravity are e.g. formation of mountains, the circulation of water and movements or convection in the atmosphere and the oceans.

The force gravity has even influenced our way of thinking. Through the years, the idea of avoiding gravity and become weightless - to “float around in the Space” - has been only a distant dream.

The cover picture of these notes shows such a dream which has been pictured by the Norwegian artist Frans Widerberg. It was painted in the 1960’s, when man had taken the first step into Space; we should remember the Space journey with the Soviet cosmonaut Jurij Gagarin in 1957. The original of this picture was a gift from Norway to the European Space Agency, ESA, in connection with Norway’s entering ESA in 1987. The picture shows humans floating in Space, apparently without any problems, and apparently without gravity dragging their bodies towards the earth.

Among the more famous writers, who have given us imaginative presentations of weightlessness is of course the French author Jules Verne (1828-1905). We will get the occasion to come back to him, and will here only mention his book about the journey from the earth to the moon, where the crew enters a state of weightlessness and floats around in their space ships, see figure 1.1.

Figure 1.1.
Illustration from the novel «De la Terre a la Lune» by Jules Verne, 1865. The Space craft, starting its flight from Florida has just arrived at a point between the earth and the moon where the gravitational attractions should be balancing each other and the crew will experience weightlessness.

1.2 The law of gravity.

A systematic study of the force of gravity and a mathematical formulation of it, was first given by Isaac Newton (1642-1727).

It has been said that as Newton saw the famous apple fall, he got the inspiration to assert that at the same time as the apple fell towards the earth, the earth fell towards the apple. According to Newton it was possible to give a quantitative formulation to the forces involved. The general formulation, which Newton published, is what has been called the *law of gravity* and is stated in the following formula:

$$F_{grav} = \mathrm{G}\,(Mm)/r^2 \qquad (1)$$

The formula gives an expression of the force, F_{grav}, which is a vector quantity (see next page) and whose direction is along the straight line between two masses (masspoints). G is Newton's gravitational constant. The two quantities, m and M, are the two interacting masses while r is the distance between their centers of gravity. In the above example, with the apple falling towards the earth, the mass of the apple is m while M is the mass of the earth. The distance from the center of the earth to the center of the apple is more or less equal to the radius of the earth R_0.

Some useful numerical quantities have been collected, and are shown in table 1.1:

Table 1.1: Some constants

R_0	The average equatorial radius of the earth	$6{,}371 * 10^6$ m
R_{eq}	The equatorial radius of the earth	$6{,}378 * 10^6$ m
R_{pole}	The polar radius of the earth	$6{,}3562 * 10^6$ m
M_{earth}	The mass of the earth	$5{,}98 * 10^{24}$ kg
ρ_{earth}	The average density of the earth	$5{,}517 * 10^3$ kgm^{-3}
G	The universal gravitational constant	$6{,}67 * 10^{-11}$ m^{3}kg^{-1}s^{-2}
g_n	Standard gravitational acceleration	9,80665 ms^{-2}
g_{eq}	Gravitational acceleration on the equator	9,78 ms^{-2}
g_{pole}	Gravitational acceleration at the north pole	9,833 ms^{-2}
g/g_n on the surface of planets:	Mercury	About 37 %
“	Venus	“ 89 %
“	Earth	“ 100 %
“	Mars	“ 38 %
“	Jupiter	“ 265 %
“	Saturn	“ 114 %
“	Moon	“ 18 %
	The average distance between earth and moon	384 400 km
	The diameter of the moon	3 476 km
ρ_{moon}	The density of the moon	3 340 kgm^{-3}
	The average distance between earth and sun	149 600 000 km
	The diameter of the sun	1 392 000 km
M_{sun}	The mass of the sun	$1{,}99 * 10^{30}$ kg

The law of gravity may also be expressed in another form. If GM/r^2 is denoted $g(r)$ and G since and M are assumed to be constant (on the Earth) , we get from (1):

$$F_{grav} = g(r) \cdot m \qquad \text{with} \qquad g(r) = (GM)/r^2 \qquad (2)$$

From this formula it can be seen that g is a quantity varying with r, which was the distance between the two bodies. This dependency is emphasized when writing $g = g(r)$. g is denoted the *gravitational acceleration*.

It can further be seen that the gravitational acceleration g is decreasing as r is increasing, and this decrease is of the second order of r. If $r = R_0$, the radius of the earth, then $g = g_0$. At a height of two earth radii from the centre of the earth, the force of gravity will be one fourth the magnitude at the earth’s surface, at three earth radii it will be 9 times smaller etc.

The shape of the earth differs from that of a perfect sphere; there will thus be some variations in the value of g over the surface. The rotation of the earth also means that centripetal forces come into play. The poles are closer to the centre of the earth than the equator which makes g greater at the poles than on the equator, see Table1.1.

Formula (2) is written in a way that is strongly connected with Newton's works on forces of inertia. In his works on general mechanics Newton showed that when a force is acting on a body with mass m, the body will achieve an acceleration $\boldsymbol{a}$:

$$\boldsymbol{F} = \mathrm{m} \cdot \boldsymbol{a} \qquad (3)$$

Here the bold symbols indicate vectors, the force $\boldsymbol{F}$ has the same direction as the acceleration $\boldsymbol{a}$. A comparison of the two formulas (2) and (3) emphasizes that $g(r)$ is an *acceleration* measured in the same units as acceleration: m/s^2. A rewriting of formula (2) using vector symbols could be

$$\mathbf{F}_{\mathrm{grav}} = m \cdot g(\mathrm{r}) \cdot (\mathbf{r} / \mathrm{r})$$

For man, who has been living rather close to the earth's surface, it has been natural to try to measure the magnitude of $g(R_0)$. Because R_0 is fairly close to a constant (see Table 1.1.), one may as a first approximation consider $g(R_0)$ to be a constant, called the *acceleration of gravity*. The symbol for g(R) has varied a lot, but for many years the symbol g has been used, and will be used in this text. One may also define a standard-acceleration of gravity, g_n. This value is mostly taken as the acceleration of gravity at the sea level at 45 degrees northern latitude and is often specified as 9,816 m/s^2. There is confusion in the literature as to the use of the abbreviation g or G for the gravitational acceleration of the Earth. In much new physiological literature G is used, while physicists usually reserve G for the constant in the law of gravity (1).

Usually the term *microgravity* does not indicate 10^{-6} g_n. The term is simply used to indicate "small g- acceleration", i.e. the prefix micro is used in the usual sense of something that is very small. The terms "microscope", "microbiology" etc are other examples of the everyday meaning of the prefix "micro". Nowadays "microgravity research" and "microgravity" means very low g conditions, and in the International Space Station it usually means e.g. about 10^{-4} g. We should also remember that in spacecrafts with no crew it is possible to achieve microgravity of about 10^{-6} g_n for long experimental times.

Formula (1) tells us that the force of gravity will in principle not become zero until R gets infinitely large, that is when we are at an infinite distance from the earth. If now the gravitation is always present at the earth's surface or in its nearest surroundings, how could we then achieve weightlessness?

Before discussing this, let us observe a comment on the notation again (from Salisbury, F.: "Units, Symbols and Terminology for Plant Physiology", 1996). CGPM is the abbreviation for «Conférence Générale des Poids et Mesures», which represents 52 member states and 26 associated states and defines the units and procedures in the SI-system).

> **Equivalent of Gravity at the Earth's Surface.** It is common for biochemists and others to express the acceleration experienced by a sample being centrifuged as multiples of the average acceleration caused by gravity at the earth's surface. There has been almost no agreement, however, on the symbol that should be used for this value. On sees in various publications: G, g, *g*, **G**, **g**, ×g, and no doubt others. The problem with these symbols is that g is the symbol for gram, G is the prefix symbol for giga, and italics (*g*) is reserved for physical quantities rather than units. **Bold facing** has no precident in the use of units. Actually, there never should have been a problem because the CGPM established the *standard acceleration due to gravity* in 1901 and confirmed the value in 1913. The primary and secondary sources show the symbol g_{n}. The logic of this symbol is that the *acceleration of free fall* (g) is a physical quantity (hence *italics*) that can have any value (units: $\mathrm{m \cdot s^{-2}}$), but the *standard acceleration of free fall* (indicated by the subscript, which is not in italics: $g_{\mathrm{n}} = 9.806\ 65\ \mathrm{m\ s^{-2}}$) is the value of particular interest. It must be experimentally determined and is thus a noncoherent unit, but multiples of this value can be used to describe the acceleration caused by centrifugation (e.g., sample centrifuged for 20 min at $1000\ g_{\mathrm{n}}$) or the acceleration experienced in an orbiting satellite (e.g., $10^{-3}\ g_{\mathrm{n}}$). This symbol, in context, should be readily understood by everyone without any special explanation.

1.3 Free fall – or weightlessness.

To get the chance to perform experiments in weightlessness, we will have to create conditions in which the objects do not have a weight.

Let us start with an experiment on the Earth. We have a mass, a heavy ball, connected to a spring and a scale, as depicted in figure 1.2A.

The spring will be more or less lengthened depending on the size of the mass. We can calibrate the system and use it to measure masses. If this mass-spring system is now moved into an elevator, as in figure 1.2B, there will be no difference in the length of the spring and an observer will conclude that the weight of the ball is the same as earlier.

The wire, which ties the elevator to the ceiling, is now cut off and the elevator will consequently fall down towards the ground. The spring will retract and an observer inside the elevator will no longer see any lengthening of the spring. On the contrary, the spring will be

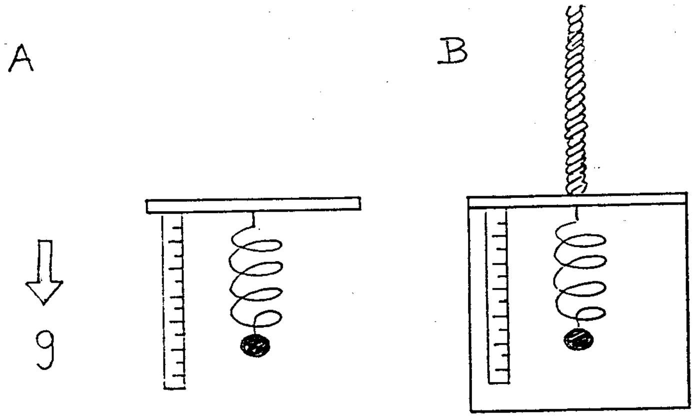


Figure 1.2. To the left, A, a mass is hanging in a spring and the gravity g (arrow!) causes the spring to stretch; the magnitude of the mass is possible to estimate by the resulting length of the spring. To the right, B, the whole system is kept in an elevator at rest, the elevator hanging in a wire. The spring is, of course extended in the same way and to the same amount as in figure A.

unloaded and the situation will be as in figure 1.3B. As a comparison the situation with the intact wire is shown in figure 1.3A.

From a physical standpoint, the important thing to observe is that the situation in Fig 1.3B is that of *free fall.* Observe that the mass is still acted upon by the gravity! All masses in the elevator are falling due to the gravity.

The velocity v of the elevator will increase but this is not our point for the time being!

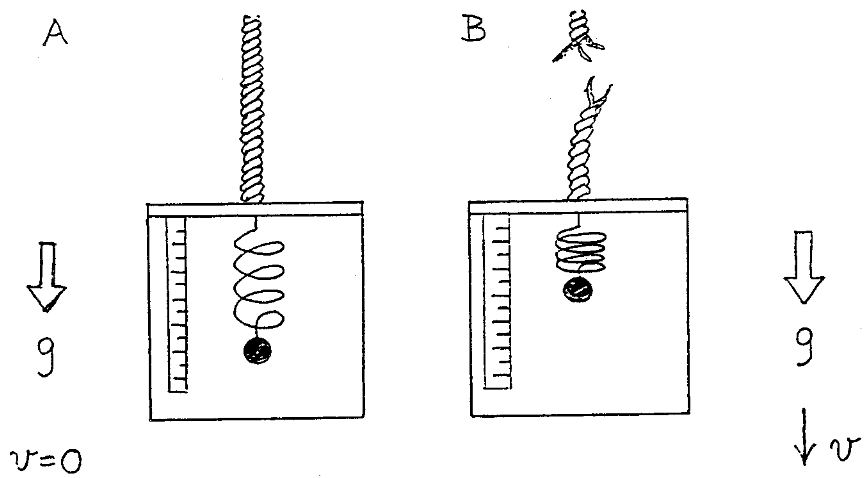


Figure 1.3. The figure to the left is identical to the one in Figure 1.2B. We note that the elevator is not moving, i.e. its velocity $v = 0$. To the right, the wire of the elevator is cut and the elevator is accelerated towards the mass centre of the earth under the influence of the gravity. The velocity is no longer zero. The system accelerates, one has so-called *free fall conditions* and the spring will no longer be extended. Under ideal free fall conditions one has weightlessness conditions (but observe that the gravity is still present, as in Figure B above!)

In the situation where the elevator wire is cut off and the elevator falling, the observer in the elevator will draw the conclusion that the mass does not have any *weight* (the spring is not extended at all), *it will be in a weightless state*. The most suitable and might be less confusing term to describe the physics of this situation is *free fall,* as introduced above. Both the elevator and its content are in a state of free fall as long as the acceleration towards the earth's surface is not counteracted by, for example, air resistance. The velocity will of course increase all the time and sooner or later the elevator will hit the earth's surface; but let us assume that the elevator falls freely towards the earth for such a long time that we have time enough to carry out interesting experiments in it!

This way of achieving free falling conditions, or weightlessness, is used in modern space technology. At several places on the earth one has installed high towers, typically 100m high, in which one allows an experimental box to fall freely in a big (evacuated -low pressure) tube, before it slows down and the free fall experiment is finished. We will come back to such laboratories.

From Newton's elementary mechanics we have learned that a body that is uniformly accelerated freely by the constant force of gravity *g,* will achieve a velocity given as:

$$v = g \cdot t \tag{4}$$

where *g* is the acceleration of gravity. The velocity *v* will then grow in time according to formula (4) (supposed the object is falling from rest). The distance the object has fallen, i.e. the distance from the top of the drop tower, will be easy to calculate:

$$\text{distance} = \frac{1}{2} g t^2 \tag{5}$$

With a tower of height 100 m, the fall time will be approximately 4,5 seconds. This means that the tower does not allow long term experiments!

Exercise 1.1

Introducing directions in our tower calculation, one conventionally designs the x,y-plane to be the horizontal one and the z axis to be directed upwards. This means that the acceleration due to gravity $d^2z/dt^2 = -g$.
We drop our experiment from the top of the tower and give the top position a z-reference value of z = 0. Solving the differential equation $d^2z/dt^2 = -g$ will give us negative values of z. Check that z = - 100 [m] produces the correct drop time!

To get a free fall we must also remember that the air friction should be avoided. In modern free fall towers one therefore evacuates the drop tube prior to the experiment (pressure achieved about 1 Pa, i.e. about 1/10000 atmosphere). The air friction will then be negligible for most experiments.

Footnote: Sometimes you find that authors are defining weightlessness only for the cases that there is no resulting gravitational force on a body, e.g. for the case when r -> ∞ in formula (1) or when two gravity vectors are annihilating. This practise is not adopted here.

1.4 Drop towers. Free fall in parabolic flights.

The time for a free fall experiment in a drop tower is clearly dependent on the height of the tower, as we have seen. The highest drop tower in Europe is the one in Bremen, Germany, see

Figure 1.4 Drop tower in Bremen.

Its height is about 150 m but the one available for scientists is 122 m. The payload is limited in size and the experiment case to be transported to the top of the tower and then dropped is seen in Figure 1.5.

Figure 1.5. Close up of experimental case and the container placed in position for a drop.

The landing of the experimental case has to be non-destructive and without hurting the payload (which might be used repeatedly in some experiments). One can use magnetic decelerations or in practice the case is falling freely into a container with small plastic spheres taking up the energy in a smooth way.

We will now look at an extension of the free fall facility. We have up to now let the experiment case fall freely down - in the (negative) z-direction and with the initial velocity $v_z = 0$. In principle, we could of course give the box an initial velocity that is different from zero. The equation describing the motion will be a slight extension of equation (4)

$$v_z(t) = - g\cdot t + v_z(0) \qquad (4')$$

If we, standing at the bottom of the tower, give the experimental case a starting speed upwards (like a rocket) it will reach a maximum height and then fall down exactly as before. The advantage of this approach is that *the case is in free fall from the moment that the 'upward push' is zero and until it touches the ground again.* Solving the differential equation $d^2z/dt^2 = -g$ with the new velocity boundary gives us a well known expression.

$$z(t) = - (g \cdot t^2)/2 + v_z(0)\cdot t + z(0)$$

$z(0)$ can conveniently be defined as zero at the bottom of the tower (surface of the earth).

By giving the experimental case a pneumatic push upwards it will be in free fall during most of its journey up to the top of the tower and in addition during the whole trip down from the tower top. A technical facility of this type was installed after some years in the Bremen tower and the total free fall time is now doubled to about 9 seconds. This is very valuable time for many experimentalists, e.g. in metallurgy.

Some details of the catapult system as well as relevant dimensions are given in Figure 1.6.

The catapult system accelerates capsule masses (from 300 to 500 kg) to a speed of 48 m/s within 0.28 seconds. The University of Bremen facility serves mostly European scientists and on average 400 drop experiments are performed each year (2010). The catapult system provides about 9.5 seconds of free fall conditions.

1.5 Free fall in parabolic flights.

Which practical possibilities do we have for longer periods of free fall and weightlessness? The drop tower possibility has been mentioned, also the catapult system developed. Extending the last possibility we can think of a launch of a bigger system, a rocket which usually (and approximately) follows a *parabolic orbit.*

The motion of a body falling towards the earth under the influence of gravity and *with gravity as the only force acting on it*, will usually be described as an elliptic orbit with the mass point of the earth in one of the focus point of the ellipse. But if we make an assumption

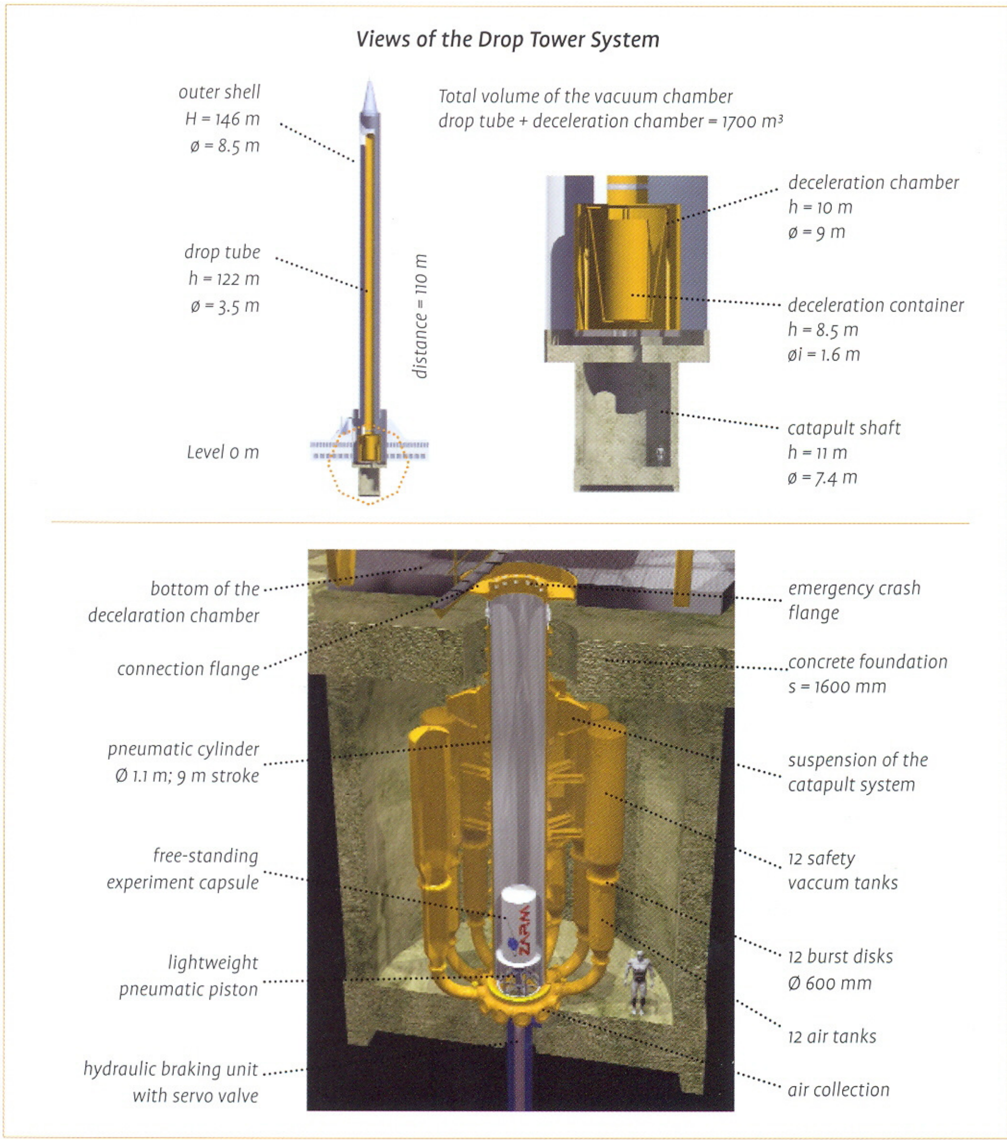


Figure 1.6 Details on the Bremen drop tower and its catapult system.

and assume that we are launching a rocket from a horizontal, flat earth where gravity acts perpendicularly to the plane and downwards, then the orbit of the rocket can usually be (approximately) described by a *parabola*.

In the practical case of a rocket launch the orbit will be in three dimensions, but we can discuss the orbit with two dimensions: the z-axis directed as 'upwards' as in the drop tower and a perpendicular axis, denote it x. When treating the drop tower we imagined letting an experiment box fall freely down - in the z-direction - with the initial velocity $v_z = 0$. In principle, we could of course give the box an initial velocity that is different from zero. The equations describing the motion will be a slight extension of equation (4'):

$$v_z(t) = - g \cdot t \ + \ v_z(0)$$
$$v_x(t) = v_x(0)$$

$v_z(0)$ and $v_x(0)$ - the components of the starting velocity – are now added.

Figure 1.7 shows some examples of such motions; the difference between the orbits is simply that the initial velocities v_z and v_x are given different values. The movement studied in the drop tower, with the initial velocity v_z equal to zero, is just a special case of the parabola movement, look at the very right part of the figure!

If we launch a rocket it will be affected by the force of gravity and the force from the rocket engines as long as the engines are in function. When the engines are switched off, only the force of gravity will, ideally, be acting on the rocket and its payload. Everything will from that moment on be in free fall, see figure 1.7. In *rocket experiments* the time available for an experiment in weightlessness can be several minutes. The TEXUS project of ESA is a sounding rocket program with the primary aim to investigate the properties and behaviour of materials, chemicals and biological substances in a microgravity environment and gives around six minutes of microgravity. MAXUS rockets reach a height of more than 700 km and have a microgravity period of up to 14 min (payload up to 785 kg). Both systems are part of ESAs activities and are launch from Esrange Space Center outside Kiruna.

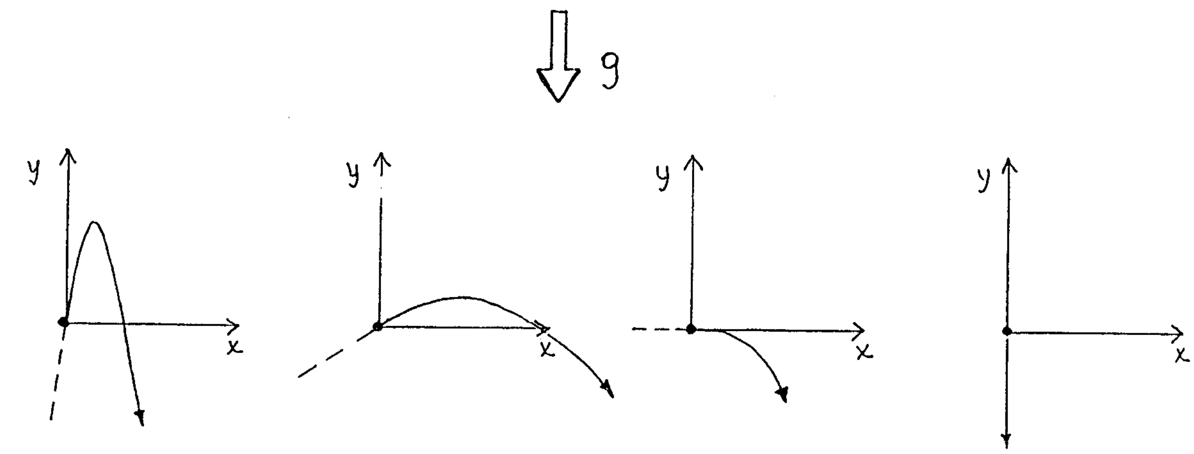


Figure 1.7. Different parabolic trajectories.
The figure illustrates the trajectory of a rocket that is accelerated upwards (broken line), the motor suddenly switched off (at the origin), and then moves under free fall conditions (full line). In free fall, the x-position is simply given by $x = v_{x,0}\,t$. The z-coordinate, on the other hand, will be determined by an equation $z = gt^2/2 + v_{z,0}\,t$ since only the acceleration *g* in the plumb line direction is acting.
In the two figures to the left the z-component of the velocity, $v_{z,0}$, is non-zero; in the two figures to the right it is zero. In the fourth figure (far right) both $v_{z,0}$ and $v_{x,0}$ are zero and we have a situation as in a free fall tower with the load falling from the top.

Another possibility to get free fall experiments is by letting an aircraft accelerate steeply upwards and then turn off the engines. The plane will then move in a parabola, and again one may get free fall conditions. Both the European and the United States Space Agencies have special aircrafts that can go through such parabolic flights, each parabola permitting a free fall time of about a few minutes.

Most often one is not satisfied with only one such parabolic orbit, but allows the aircraft to go up and down following a wave motion with about 25 individual parabolas (in between the free fall periods the aircraft then has to accelerate!). The researchers can use such flights to test their experiments during the intervals of free fall. Often this is a precondition for being allowed to carry out the experiments during more extensive space journeys, e.g. in the Space shuttle.

Figure 1.8 shows a NASA-jet plane that is being used for tests in weightlessness. The acceleration that the payload will experience is also shown. This profile applies to the z-direction of the plane, and it can be seen that the acceleration varies from almost weightlessness to 2g when the plane is accelerating.

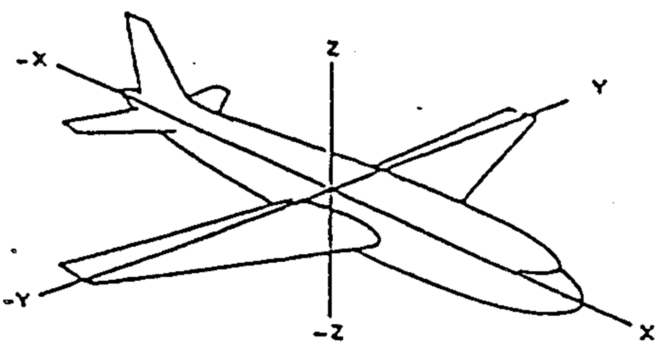
Exercise 1.2

The differential equation for an experiment in a drop tower can be written

$$d^2z(t)/dt^2 = -g$$

Assume that we use the catapult system with a launch speed of $v_z(0)$ such that the experimental case can reach a maximum height of z_{max} (in the Bremen drop tower this is roughly 100 m). Choose $z(0)$ to be = 0 and t = 0 at launch.

Discuss, by solving the differential equation, the value required on $v_z(0)$ and the time for the experimental case to reach firstly z_{max} , and secondly to be back at level $z = 0$ again.



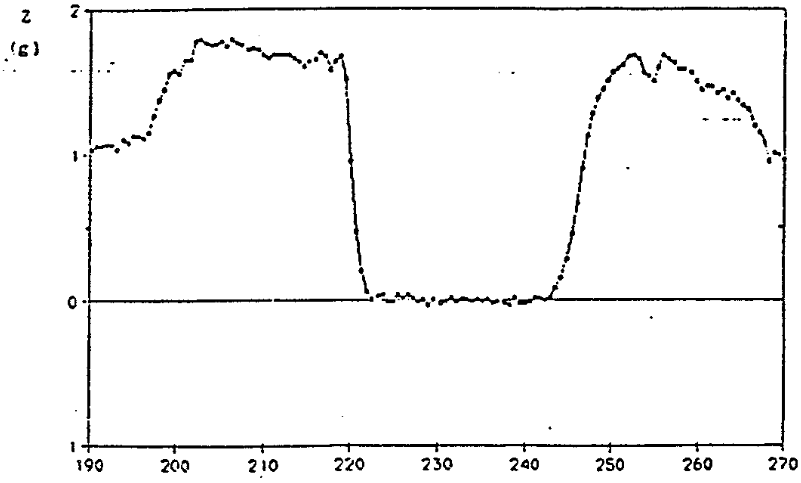


Figure 1.8. Parabolic flight of air plane. Acceleration (in *g*'s) as a function of time (s)
A NASA air plane, specially equipped for free fall experiments is depicted. With a coordinate system as in the middle figure, the acceleration profiles of the lowermost figure can be recorded for parts of a flight. During a time span of about 25 s the acceleration in the z-direction is close to zero, during the other phases the it reaches about 1.8 g_n (left scale).

1.5 Free fall in satellites - spacecrafts in circular orbits.

The methods to achieve free fall conditions that we have discussed clearly have their shortcomings. We will consider an alternative method by first studying a picture from Newton's work on mechanics, "Philosophiæ Naturalis Principia Mathematica" ("Principia", 1687). Figure 1.9 represents an imaginary situation where we are standing on the top of a mountain V, firing bullets horizontally to the right.

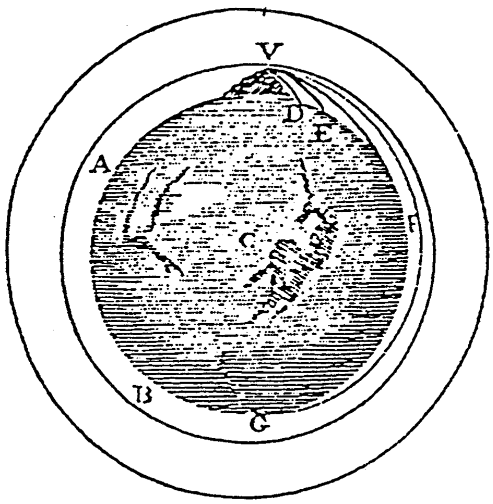


Figure 1.9. Picture from Newtons book on mechanics, 1676. A person is thought to be placed on the mountain tip V. Cannon balls can be fired from that tip towards the right, landing on different spots, see text.

Our first bullet, fired in the horizontal direction will travel some distance to the right. Due to the gravity, it will of course *be attracted to the center of the earth* and hit the earth's surface at point D. If we increase the initial velocity of the bullet, it will reach a bit further, to the point E. With an even greater launch velocity, the bullet will get even further and hit the surface at point F: The curvature of the earth allows the bullet to be in an orbit almost parallel to the earth-surface for a longer time than earlier. If the launch velocity is increased even more, the bullet will drop down at point G.

Observe that the gravity acts towards the centre of mass of the Earth, the attraction vector is rotating with the bullet. (In the case of the parabolic approximation that we discussed earlier it was assumed to act in a fixed direction in space).

Now, if we reach a proper velocity the bullet will fall towards the centre of the earth in a way that exactly fits the curvature of the (ideal) earth surface. As a result the bullet will go around the earth at a given altitude (or properly at a certain distance r from the mass point of the earth). Two such orbits are traced in Newton's figure, the inner one named VBAV together with an outer one.

The bullet now follows a *circular orbit*. The force necessary to keep it in this orbit is *the centripetal force F_s*, which according to Newton may be written in the following way:

$$F_s = mv^2/r \qquad (6)$$

The v is the velocity of the bullet in its orbit, the so-called *orbital velocity*. As before, r is the distance to the centre of the earth.

The centripetal force F_s, necessary to keep the bullet in the circular orbit, is provided by the gravity pull on the bullet. We have earlier discussed the formula (1) for the force of gravity, which is acting on the bullet and attracts it to the earth. When the centripetal force just balances this force of gravity, the bullet will move in a stable circular orbit. *During all the time in orbit, the bullet will be accelerated towards the earth's centre of gravity and will therefore be in free fall (no air friction etc. is considered).*

If we imagine a satellite instead of Newton's bullet we have, in fact, found a way of getting a satellite laboratory that will always be in free fall. In this laboratory we may then work out all the experiments in weightlessness which were impossible to perform during the short free fall time in, e.g., a drop tower.

Formula (6) gives us the possibility to calculate the magnitude of the orbital velocity the satellite must have if the centripetal acceleration should exactly balance the force of gravity. We get:

$$F_s = F_{grav} \quad \Rightarrow \quad mv^2/r = mg(r) \quad \Rightarrow$$

$$v = \sqrt{r \cdot g} \qquad (7)$$

If we assume an orbit close to the surface of the earth, $r = R_0$ and $g = g(R_0) = g_0$ and with tabulated values for R_0 and g_0, we find *the orbital velocity to be about 8000 m/s.* This is thus the speed necessary to keep a satellite in orbit just above the Earth's surface. If one can not achieve this speed, the satellite can not circle around the Earth in a stable orbit. This fundamental limit is denoted *the first cosmic velocity.*

The time it takes for such a spacecraft to go around the earth while moving in an orbit just above the earth's surface is also quite simple to calculate. We know that the satellite travels a distance of $2\pi R_0$ during one revolution. Since we also know the velocity (from formula (7)) the time period - i.e. the period of one revolution – becomes:

$$T = 2\pi R_0 / \sqrt{R_o g} \;= 85 \text{ min} \qquad (8)$$

From experience with the Space Shuttle it is worth remembering that when the Shuttle was in circular orbit it had an altitude of about 290 km above the earth's surface, and the period of revolution is then about 90 min. What is then the period time of the International Space Station?

1.4 The orbital period of satellites – an extension.

The previous section dealt with the orbital period of a satellite in circular orbit with the distance R to the centre of the Earth, cf. formula (8).

The relationship between the altitude of the orbit and the period of one revolution around the earth may be calculated in a more general case with the use of formulas (1) and (6):

$$\text{constant} \cdot \frac{m}{r^2} = \frac{mv^2}{r}$$

v^2 is thus proportional to 1/r. Using the fact that $v = 2\pi r / T$ we find that T^2 is proportional to r^3. One can reformulate this

$$T^2 = \text{const} \cdot r^3 \qquad (9)$$

Taking the logarithm of both terms we get

$$2 \cdot \log(T) = 3 \cdot \log(r) + \text{constant.}$$

The second power of the orbital period is thus proportional to the third power of the distance to the center of the earth. This relation may be drawn into a diagram with logarithmic axes to give a straight line. This is done in figure 1.9.

The slope of the straight line in the figure is 1.5 (since formula (9) may be written with T proportional to $r^{3/2}$ (and then log(T) = 3/2 log(r)). The unit on the x-axis is R_0 (the radius of the earth) and on the y-axis T_0 (the time to travel one revolution around the earth). Three different points, A, B, and C, have been marked on the line:

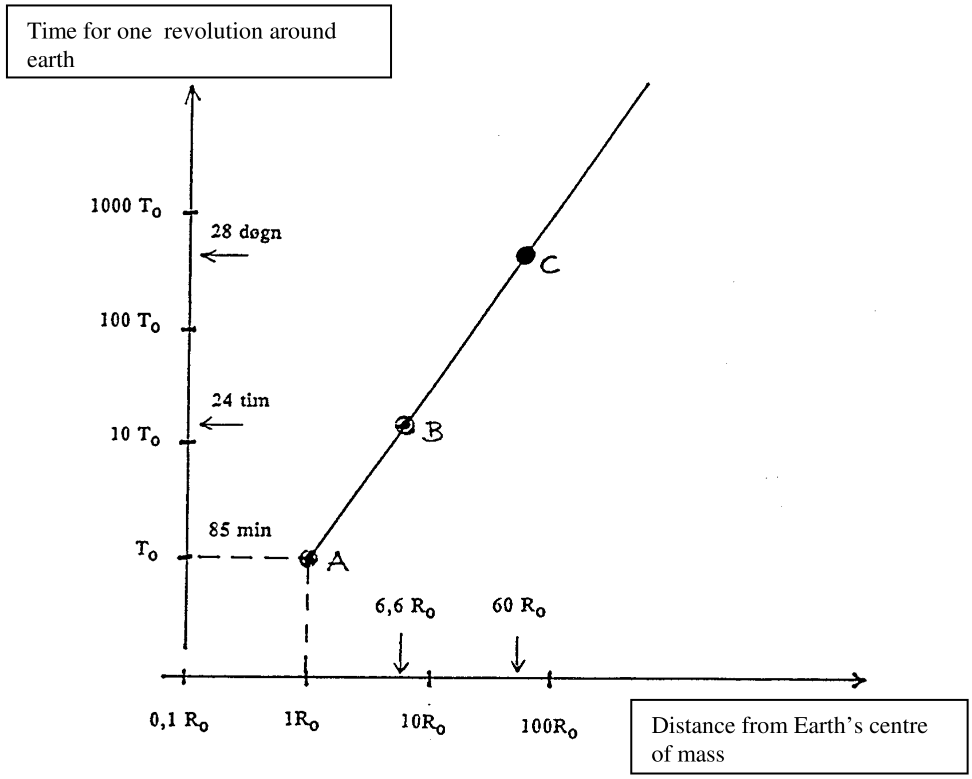


Figure 1.9. The axes are both logarithmic ones and the straight line, therefore, implicates a linear relationship between the time for one revolution of a satellite and its distance to the centre of the earth. T_0 indicates the time for one revolution when the radius is equal to the Earth's radius R_0

Point A indicates the orbital period and the orbital radius of a satellite or a spacecraft staying just above the earth's surface. In section 1.3 this period was calculated to be about 85 min. The matching radius is that of the earth, R_0, so it will then be logical to mark out the orbital period as T_0 on the axis. The approximation of R_0 used in calculations is often 6400 km (cf. Table 1.1). Since a spacecraft cannot be somewhere below R_0, the line ends in point A.

Point B corresponds to a satellite with a period of revolution equal to 24 hours (or about 16 T_0). Such satellites will thus have the same rotation speed as the earth and if they are placed in the equatorial plane, they will always remain at a fixed position with respect to the earth. They are named *geosynchronous satellites*. Their position above the earth's surface is about 6,6 earth-radii, measured from the center of the earth.

The last point, C, represents a satellite with a orbital period of about 28-29 days and nights. This satellite therefore corresponds to the satellite commonly called the moon. As also indicated in the figure, the distance from the earth to the moon is about $60 \cdot R_0$.

We have made several implicit assumptions in our discussion. The mass of the Earth is assumed to be very big compared with that of the satellite. G and M are assumed to be constants (the structure of the Earth certainly means that there are local variations of the gravity) and no perturbations occur from other celestial bodies (the sun for example). But all such complications set aside, the satellites mentioned fall freely towards the earth's center of gravity. In our calculations, factors that may affect the shape of the orbit, like for instance the fact that the atmosphere will slow down the motion, are not taken into consideration.

As already mentioned the line ends at the distance R_0, which corresponded to a satellite moving at zero height above the earth's surface. But we may ask if it could be possible to extrapolate the line to shorter distances from the earth's center.

Exercise 1.3

A small satellite is orbiting a planet with dimensions identical to the one our Sun (se Table 1.1). The density of the planet is ρ_1. Another small satellite is orbiting a much smaller planet, with dimensions equal to those of our moon, and with a density of ρ_2.

The satellites go in circular orbits. What is the ratio between the two orbital periods of the satellites, i.e. T_1/T_2?

Exercise 1.4.

At a distance of $R_0/2$ from the earth's mass center and in the plane through the equator, an enthusiastic student has dug a cylindrical (or properly a toroid) tunnel around the mass centre of the earth. Because he wanted to get an orbiting satellite into the tunnel, he made it big enough for a small satellite to fit into it.

In this underground "doughnut" - like tunnel case, what would the satellite's orbital period be, and where (in figure 1.9) would you plot the spacecraft?

If the tunnel is situated at an arbitrary distance from the earth's center (i.e. not at $R_0/2$) but still below the surface, what would the period of revolution be?

1.5 Short comment on elliptical orbits.

In reality the satellite orbit is usually not exactly a circular orbit, a fact discovered several centuries ago. Studying the orbits of the planets around the sun Kepler (1571-1630) found that the planets followed in fact *elliptical* orbits (to a remarkably good approximation). An ellipse has the general shape depicted on the next side.

We need only to remark that Kepler found that a planet, position X in figure 1.10, moves around the Sun being in one of the focus points, **F1** or **F2**. The semi major axis a is half the major axis AB, which thus has a length of 2a, the minor axis CD is 2b. The distance between the two foci is denoted 2c. The eccentricity e is the ratio between this distance 2c and the length of the major axis, 2a. The eccentricity of the ellipse is then less than one, and goes to zero when the ellipse changes into a circle. When this happens the orbit is a circle (F1 coincides with F2 and c = 0) and the radius r equals a, which is then also equal to b.

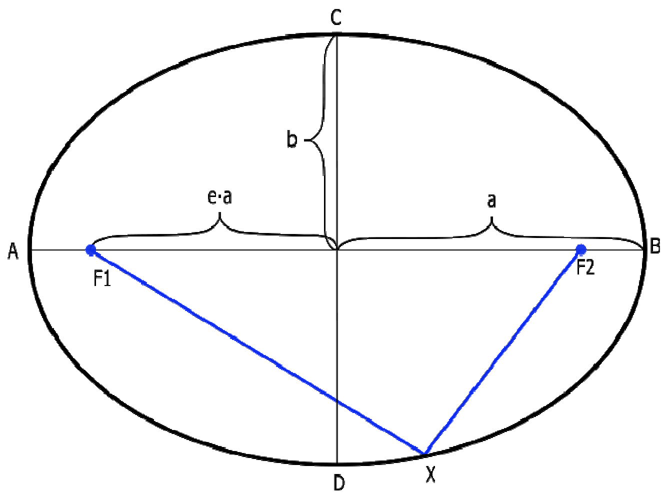


Figure 1.10 Elliptic path of satellite around the earth or planet around the sun. In the figure the distance a is half the major axis, b half the minor axis. The figure denotes the distance between the two focal points 2 e•a. This introduces the *eccentricity*, e, of the ellipse as e = 2c/2a = c/a, where c = e•a (as used in this figure).

Kepler formulated three laws that describe the motions of the planets. In a short version they may be expressed as follows:

1. Each planet moves in an elliptical orbit, with the sun in one focus of the ellipse.

2. A line from the sun to the planet sweeps out equal areas in equal times.

3. The orbital periods of the planets are proportional to the 3/2 power of the major axis length of their orbit.

The expression we just deduced for radial motion, equation (9), is the special case of Kepler's third law when the ellipse has become a circle with radius r.

We have up to now looked at circular movements around the Earth, since the orbit used by space vehicles in most microgravity experiments (and also for communication satellites etc) is, in fact, close to a circular one. But in the more general case of a satellite in orbit around a mass *M*, the orbit will be an elliptic one, and we thus have to specify characteristics of the Kepler orbit of the satellite.

The starting point is of course equation (1) but we now write it in a slightly different form:

$$F_{grav} = GM\frac{m}{r^2} = m\frac{m}{r^2} \qquad (1')$$

Here μ is the so called *gravitational parameter* = $G \cdot M$ (the Gravity constant times the Mass of the Earth) = $3.99 \cdot 10^5$ [$km^3 \cdot s^{-2}$]. For elliptic orbits around the Sun the mass must of course be adequately changed.

Now, in a Kepler, elliptic, orbit for a Earth bound satellite, the *velocity* of the satellite will be a function of the radius vector from the centre of mass of the Earth. The expression for the velocity is given by the following formula

$$v(r) = \sqrt{\mu \cdot (2/r - 1/a)} \qquad (10)$$

Here a is half the long axis of the elliptic orbit.

For the special case of a circular orbit a equals the radius and we get

$$v(r) = \sqrt{\mu \cdot (2/r - 1/r)} = \sqrt{\mu / r} \qquad (10')$$

The formula is in agreement with the expression we derived for the circular orbit, equation (7). Show this!

The orbital period T, for the satellite in an elliptic orbit is independent of its eccentricity and is given by

$$T = 2 \cdot \pi \cdot \sqrt{a^3 / \mu} \quad \Rightarrow T^2 = (\text{constant}) \cdot a^3 \qquad (11)$$

Again, if we have a circular orbit a = r and we see that T^2 will be proportional to r^3. This is of course Kepler's law number 3 and is in accordance with our derived result (equation (9)) for the circular orbit.

For realistic orbit calculations one has to consider many perturbations and even if our approximation of a circular satellite orbit around the Earth is a good one, it must be improved in real orbit calculations for satellites.

1.6 Available time in free fall - weightlessness.

The possibilities for getting free-fall-conditions may now be summarized into four main groups: *drop towers, parabolic airplane flights, rockets flights and satellites/spacecraft orbiting the earth*. The last group includes spacecraft of several different types, for instance manned or not manned crafts and space stations.

A summary of different possibilities to achieve free fall conditions is shown by the rectangles in figure 1.11. The y-axis in the figure presents an attempt to describe the time available for experiments offered by the different alternatives. Finally, the x-axis describes the level of g-perturbations that are typical for the system – it will be discussed in section 1.6.

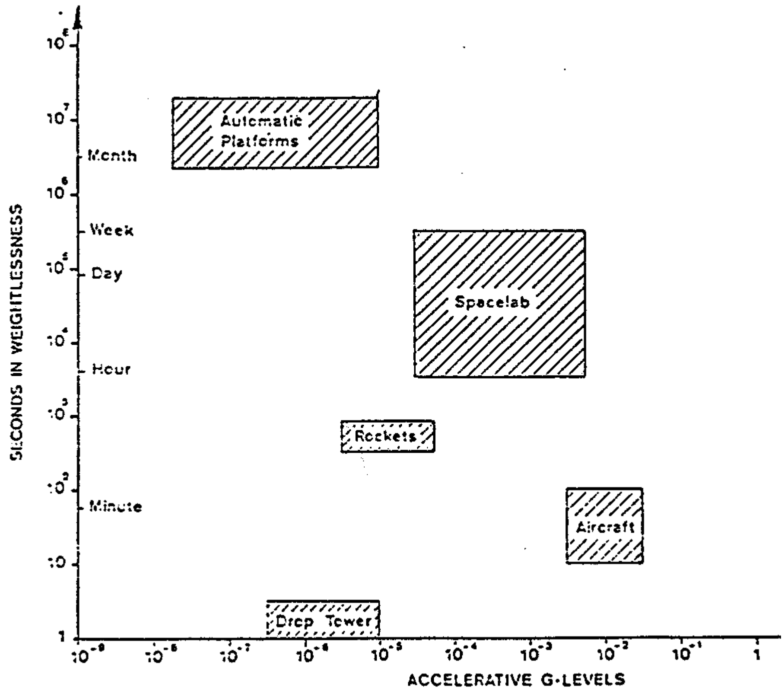


Figure 1.11. Typical values of free fall duration in microgravity of different systems plotted versus acceleration levels experienced, i.e. acceleration due to (noise) vibrations. The duration of microgravity conditions is plotted on a logarithmic scale as is the acceleration levels, measured relative to g_n.

The y-axis in figure 1.11 shows typical values of the time in free fall, given in seconds. The maximum limits should be extended: drop towers with catapult systems could be used up to about 10 seconds as we have discussed, rockets can offer somewhat longer free fall times than indicated, the International Space Station (ISS) offers, in principle, infinitely long time for free-fall experiments. The available time in the Space Shuttle was limited due to the necessary food storage and mass.

A short experiment that requires about a minute may thus be offered several possibilities: Parabolic flights, rockets, or spacecraft in orbit. For economical reasons one will probably choose the cheapest alternative, which is the parabola-flight or the rocket. An experiment that lasts for a couple of days, which is often necessary in physiological experiments, can, on the other hand, only be carried out in a kind of satellite.

Without going into details about the alternatives, it may be mentioned that space crafts are often superior to rockets in offering capacity and flexibility for carrying out free fall experiments. For many years the American Shuttle program, the Space Transportation System or the STS system, was of great importance in this connection. The space crafts were built to take different payloads, and a special module system made for free fall experiments was the one called *Spacelab*. Spacelab was designed and built by European industry through ESA. Figure 1.12 shows the dimensions of NASA's space shuttle with Spacelab as a payload. The system has been an important work-horse when it comes to experiments in weightlessness. Free-fall experiments are now (2015) most often performed on the ISS, payloads being transported to the station by Russian spacecrafts while alternatives are considered.

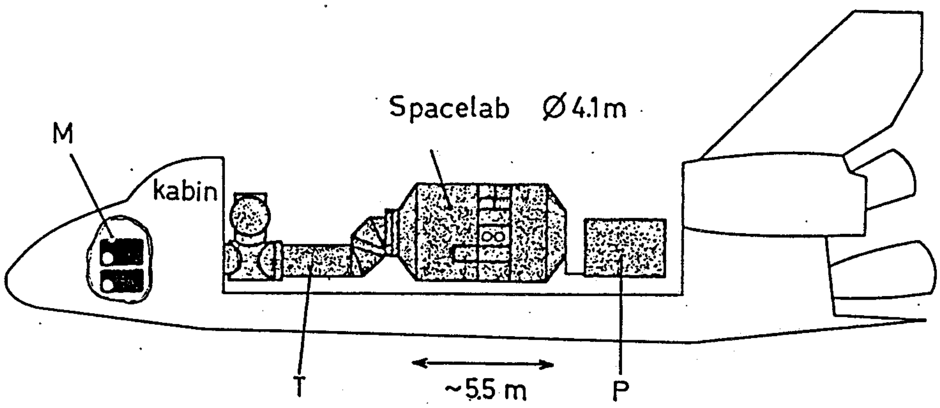


Figure 1.12. The Space Shuttle with the Spacelab. The sketch indicates the dimensions of Spacelab, but the laboratory could be extended in modules and the figure, therefore, shows only one example of the length dimensions. T was a tunnel connecting the cabin with the laboratory and P indicates an external experimental platform. M shows the location of modules that could be used for small scale experiments.

In the next section we are going to consider one technical aspect which every Principal Investigator (PI, i.e. the researcher responsible for a free fall experiment) has to consider: Which acceleration perturbations can the experiment tolerate? Or rephrased: What kind of vibrations and unwanted forces can the experiment tolerate?

1.6 Acceleration disturbances in free-fall experiments.

If a scientist wants to carry out an experiment in weightlessness, the reasons are that the force of gravity needs to be kept below a certain critical level. This critical level must be specified, and it is also important to know what kinds of perturbations, in terms of unwanted forces, that may occur during the experiment. *Acceleration forces can never be totally eliminated.*

The launch itself represents a special problem. The accelerations taking place will set up forces which, vector-wise, will add up with the gravity and will thus exceed $1g_0$. A typical maximum value during a launch of the Space shuttle was 2 - 3 g_n. Experiments in weightless condition could therefore not take place until the spacecraft had reached its orbit. A rocket launch involves much bigger accelerations, might be tenths of g_n

But perturbations will occur even when the spacecraft is circulating in its orbit. Correcting the orbit can be necessary (drag from atmosphere, temperature changes etc), or correcting the pointing direction has to be performed in order to *stabilize* the system. The needs for controlling, e.g., Spacelab led to maneuvers in the orbit and these disturbances were in the range of milli-g to 0.5 g_n. For the experiments onboard it was then important to know *when* a maneuver was going to take place.

Also mechanical *vibrations* will occur in the space vehicle. They can propagate through the vehicle and into the parts of the spacecraft where the free fall experiments are being carried out. Such vibrations – let us say from a compressor – may accelerate equipment, leading to perturbation of the experiment. The human activities in the experimental facilities may also lead to vibrations and mass accelerations: Incubators or refrigerators may be turned on and off, centrifuges may be started etc. The activity of the crew in a manned spacecraft may also be a source of vibrations. An astronaut may for instance, do physical exercises; participate in physiological acceleration experiments etc.

Vibrations are usually specified in units of g_n (i.e. in units of standard acceleration), which makes an easy comparison of the perturbation levels possible. The perturbation levels (typical values) for the different free fall alternatives are shown in Figure 1.9. In table 1.2 some of these sources and the maximum g-levels are presented for the case of the Spacelab. As shown in the table it is in reality very hard to carry out a so-called weightlessness experiment. In practice the noise level is low for most of the time but interrupted with higher noise levels.

Table 1.2: Some maximum values of acceleration perturbations specified for Spacelab.

Orbit accelerations (specifications)	<	$3 * 10^{-4}\ g_n$
Crew activity (0,1 - 3 Hz; specifications)	<	$5 * 10^{-2}\ g_n$
Deep breathing, coughing	<	$2 * 10^{-3}\ g_n$
Arm or leg rotation	<	$2 * 10^{-3}\ g_n$
Walking, jumping	<	$10^{-2}\ g_n$
In orbit maneuvers		10^{-3} to $5 * 10^{-1}\ g_n$

A special source of error is the drag or the air friction. This plays a role even if the atmosphere is fairly thin at the level of the ISS orbits (typical orbits at 400 km). The spacecraft is continuously being slowed down leading to a (negative) acceleration, which may be expressed in g_0.

The atmospheric drag effects vary according to physical flow resistance of the satellite or station construction as well as on the height above the earth. This drag acceleration implies a noise level (at very low frequency) in the ISS.

2. PHYSICAL PROCESSES IN WEIGHTLESSNESS.

2.1 Objects without weight

One situation we often talk about when considering an object in weightlessness is an astronaut "floating around" in a space vehicle. However, any loose object in a satellite will be floating around and in the free fall experienced by the spacecraft itself, the *payload* will also be in free fall.

To most of us, experiencing weightlessness would be a rather new and surprising situation. We only need to imagine everyday situations to see how used we are to the fact that everything falls towards the earth: Our food stays on the plate, which again stays on the table. When pouring milk into the glass, the milk flows down and stays in the glass. Coins are dropped into the valet; tools are put into the toolbox etc.

Let us consider a familiar example: A glass is falling onto the floor and goes into pieces. Pieces of the broken glass fly through the room and finally fall to rest on the floor, so that we may clean up. In weightlessness this situation will become rather different. If a glass is broken in a spacecraft, pieces from the glass will float around in the spacecraft without falling towards the floor. Consequently, for an appreciable time there will be a great risk for the astronauts to get glass dust into their lungs. Or, dust may come in contact with electronics and cause dangerous failures. NASA has very strict rules concerning how to react in the case of such accidents.

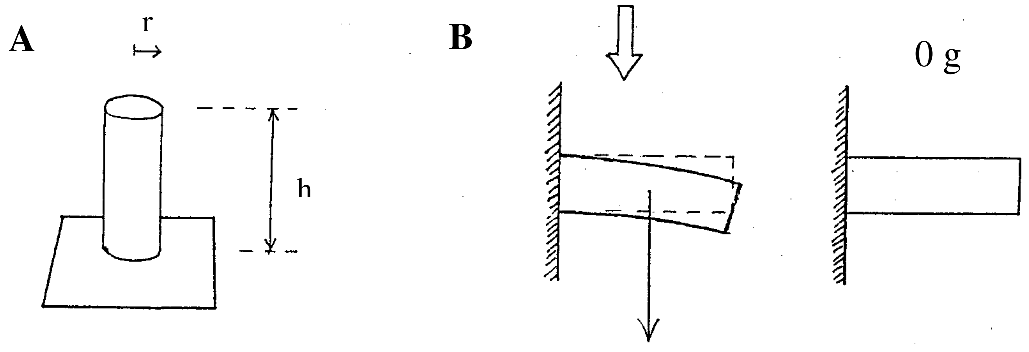
Looking back to our example of an elevator which is in free fall, Figure 1.3, we realize that the elevator passenger is placed in an accelerating system. He/she can will judge the situation as if g equals zero (or ideally this is so). Consequently, the physical laws which he/she has learnt and seen in action on the earth should be replaced with rules where g ~0. He/she will ill 'be in weightlessness' since the weight is per definition (body mass)·(g) and g is close to zero as judged from a weight! The body mass m is of course still present!

> **Exercise 2.1**: In some kinds of experiments in Spacelab it may be of interest to determine the mass of a substance or an object. Many normal balances on the ground work by having the force of gravity to attract the mass that is connected to a spring. The spring position then gives a direct measurement of the mass. However, if we are in weightlessness, this method obviously does not work.
>
> Can you imagine how a mass determination, based on other physical principles than the one mentioned above, could be performed in free fall?

We will now discuss some physical situations and processes in which gravity normally plays a role and which, accordingly, will change in free fall, in microgravity.

2.2 Changes in pressure, stress. Examples.

A force acting on a mass often gives rise to a *load* or a *pressure*. A few such simple examples are given in figure 2.1, where some different situations are illustrated.



$$M = \rho \cdot \pi r^2 \cdot h \qquad\qquad F = M \cdot g$$

Figure 2.1. Effects caused by free fall conditions.
In 2.1 A, a cylinder with mass M exerts a pressure P on the surface. This pressure will not exist in free fall. Figure 2.1 B illustrates how gravity causes a load and distortion of a cylindrical structure fixed to a wall. Under free fall conditions such effects will not occur.

A homogenous cylindrical pillar has been drawn in figure 2.1.A. The mass of the pillar is calculated when we know the density of the material in addition to its volume:

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

The *force* acting on the surface under the pillar becomes at 1 *g*: $M \cdot g$. The corresponding *pressure* (the force is assumed to be equally distributed over the bottom area) then becomes the force divided by the bottom area:

$$P = \frac{Mg}{\pi r^2} = \rho h g \tag{12}$$

When we enter the state of free fall, and thus move to an accelerating reference system (as discussed in the drop tower experiments in chapter 1.4), an observer will not discover any forces acting on the items. *This corresponds to setting g = 0 in the formula (12)*. When we enter the state of free fall the pressure P becomes zero. In the same way the pressure from heavy particles against the bottom of a physiological cell ceases in free fall.

Figure 2.1 B shows a bar connected to a wall. At 1 g_n conditions the gravity affects the bar, and as a result the bar will experience a load. The upper side of the bar will lengthen while the under side will be compressed. In free fall on the other hand, the forces due to gravitational acceleration will vanish and the load becomes zero. This is illustrated to the right in the figure.

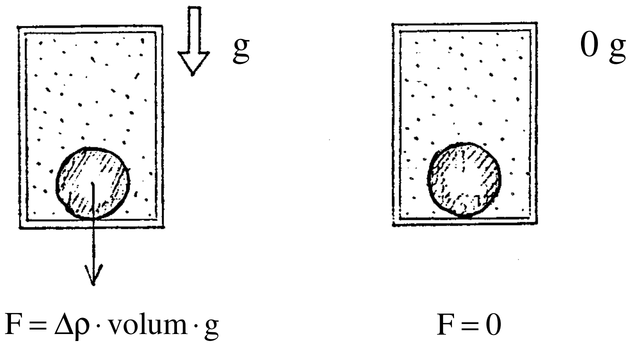


Figure 2.2. Effects caused by free fall conditions.
In the container of the left figure a sphere has sedimented onto the bottom due to the density difference (difference between the sphere and the surrounding liquid) and the presence of the gravitational acceleration g. The pressure can be calculated when one knows the force F and the contact area between the sphere and the bottom of the box.
In the figure to the right, free fall conditions occur and the force will now equal zero and at the same time the pressure will disappear.

Figure 2.2 shows how a sphere has sedimented through a fluid to the bottom of a vessel. We have assumed that the density of the sphere is higher than that of the fluid, and that it will, therefore, sink. Due to the force of gravity a certain force from the ball will act on the bottom of the vessel. Consequently a pressure, given by the magnitude of the force and the contact area, will develop. In weightlessness the situation becomes different: The pressure against the bottom will vanish. This is illustrated to the right in the figure.

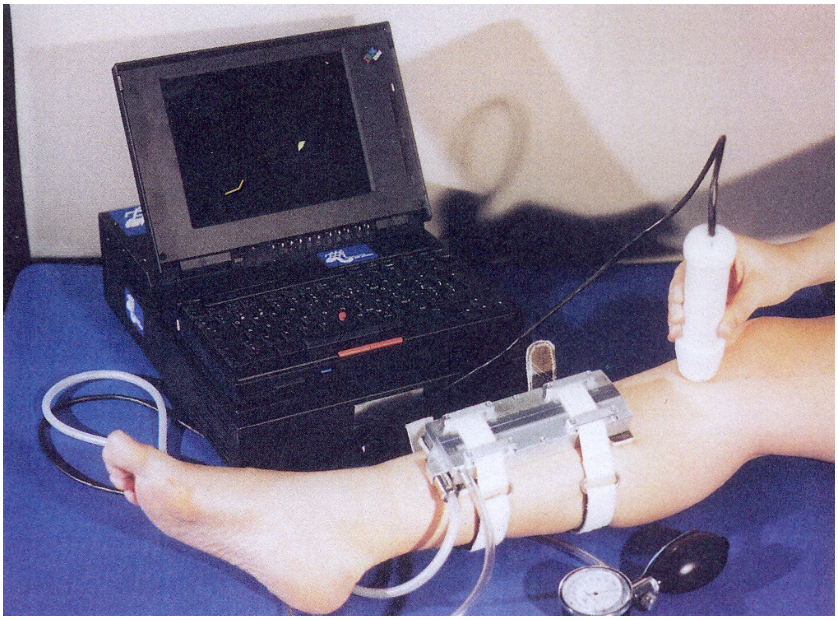


Figure 2.3 The mechanical pressure on the human skeleton is changed drastically in weightlessness. The bone structure, bone cells, bone healing etc are, therefore, important parts of science carried out in weightlessness. The measurement situation above is from development of equipment for bone structure studies.

2.3 Sedimentation and buoyancy.

Sedimentation and *buoyancy* are two aspects of the same physical phenomenon: Under "normal" ground conditions a body sinks or ascends through a fluid or a gas.

If we consider a ball with a density ρ_1 in a medium with a density of ρ_2 we may easily get forces acting downwards, due to the force of gravity, or upwards, due to buoyancy:

$$F_{tot} = F_{down} - F_{up} = \rho_1 Vg - \rho_2 Vg = (\rho_1 - \rho_2)Vg$$

As we see (and as Archimedes studied a long time ago!) the ball will sink if the density of the ball is greater than that of the fluid. This is because the force directed downwards then will become bigger than the force directed upwards. On the other hand, if the density of the medium is greater then that of the ball, the ball will rise upwards.

This means that *in the accelerating reference system (the 'free fall conditions') the force is zero; the ball will neither sink nor rise*. This is an extremely important result and perhaps we are so used to sedimentation and buoyancy, that we have difficulties to imagine the physics in free fall. Effects based on sedimentation and buoyancy are very much studied by scientists in experiments in weightlessness.

Some examples of phenomena and areas in which free fall experiments are of interest:

***a**. Heavy particle in a biological cell.*

Heavy particles in a biological cell will sediment towards the bottom of the cell, and the pressure against the lower cell membrane will increase. This principle for sensing the direction of "up" and "down" is used in the *vestibular system* of man. The vestibular system is part of our balance system and we will discuss it later.

The position of the heavy structures in the vestibular organ is normally recorded by electrical signals released by the particle pressure against the membrane. These electrical signals give information to our brain about the position of the particle. If the position of the organ is changed, the position of the heavy particles will change to a new place. The information to the brain will change and the new position will be "denoted".

Also the balance system in plants and simple organisms, like unicellulars, works according to the same principles. We will return to this in a later chapter.

In many biological cells there are structures normally oriented in different directions in the cells (*microtubuli*, *endoplasmatic reticulum*). Pressure from heavy particles like crystals, starch grains etc, may give rise to stretching of such structures, which again will be changed in weightlessness.

***b**. Drinks containing carbon dioxide.*

Under $1g_0$ conditions we are used to the behaviour of liquids with dissolved gases, e.g. beer. When we open the bottle and the pressure is decreased small gas centres are built up and are responsible for the gas bubbles created. The bubbles rise by buoyancy and the gas will escape into the air.

How would a corresponding process look like in weightlessness?

Figure 2.4 shows a sequence of pictures from a rocket experiment that illustrates the example. Try to explain what can be seen.

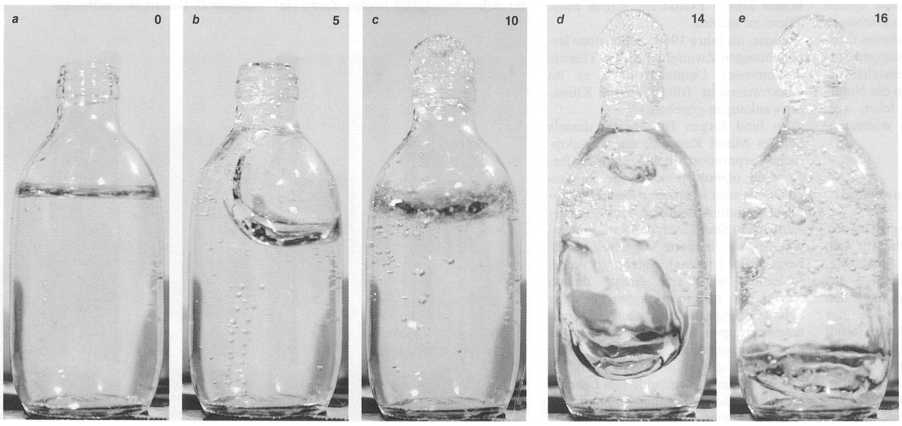


Figure 2.4. Effects caused by free fall conditions.
A liquid with gas dissolved under pressure is photographed during a rocket experiment in microgravity conditions.

The processes that occur when the bottle is opened in microgravity are very complicated. Some gas bubbles have been released before the experiment and the starting situation is as in 2.4.a. After few seconds the surfaces will curve into spherical ones (to minimize energy) and larger bubbles will also merge, 2.4. b. This occurs fairly rapidly and parts of the water moves along the inner glass surfaces of the bottle and is pushed out of the bottle (due to gas bubbles increasing their volume), 2.4.c. In 2.4.d the photo shows that a gas bubble moves back in the bottle, surrounded by liquid, that the number of smaller bubbles increases and water continues to be pushed out. In contrast to the conditions on the earth many small bubbles will be created and will merge and also stay in the bottle, 2.4.e.

The time after start of experiment is indicated: 0, 5, 10, 14 and 16 seconds.

***c**. Density differences.*

The movements of packets of water with different densities – e.g. due to different temperatures - will also depend on the g-forces under normal conditions. A water 'package' colder than the surroundings will sink under normal 1 g conditions, but this will not happen in microgravity. The example is important and will be discussed in section 2.4.

The air around an incandescent lamp is warmed up due to the heat losses from the lamp. Hot air has a lower density than the cold air of the surroundings and normally packets of hot air are transported upwards because of the buoyancy. This will not occur in weightlessness and the temperature of the lamp will be higher! (Discuss what will happen with the light intensity of the incandescent lamp!)

***d.** Pressure changes*

Pressure changes affect the human body and two illustrations can exemplify this fact. The first one is schematically depicting the spinal cord under 1 *g* conditions with typical, normal bends of the spine (Fig. 2.5 left figure, A) and after a time in weightlessness (Fig. 2.5 left figure, B). Here the spinal cord has stretched and become longer. The sketch of the blood/lung systems (Fig. 2.5 left figure, C) are also affected in weightlessness.

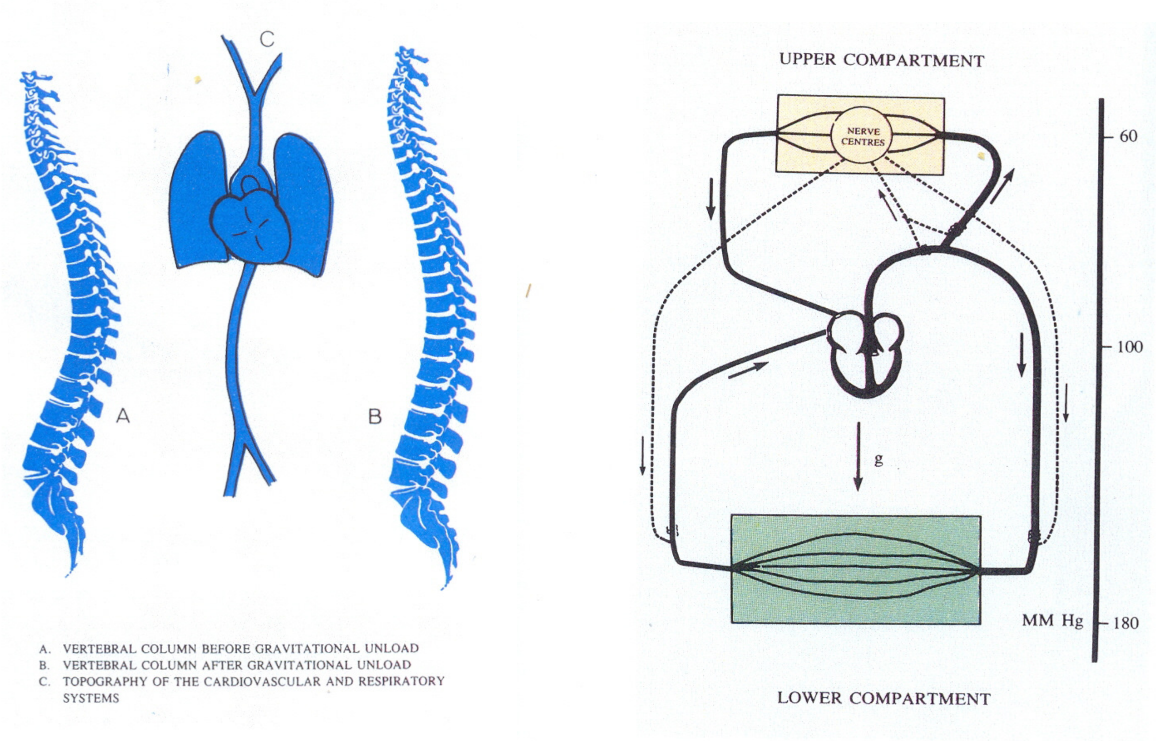


Figure 2.5. The skeleton and cardiac systems are heavily influenced by weightlessness. Explanations in the text.

The right part of the figure 2.5 details the blood pressure situation of a person, standing upright. The blood pressure levels are shown to the utmost right. The distribution of blood will be different in a person in weightlessness – as is also the case when we are resting in a horizontal bed.

We will come back to simulation of weightlessness in a later chapter but already now point at some details of one principle, used in training astronauts for operation in weightlessness.

Figure 2.6A shows a person holding an arm straight out and carrying a box filled with liquid. In the bottom of the box there is also an iron-ball. Under 1*g* conditions, many forces, exerting pressure, will act on the different sub-units in the figure. Some forces are shown and denoted F_1 to F_4. The situation is connected to conditions illustrated in figure 2.1 and 2.2. This type of p*ressures and loads will totally vanish if the system is transferred to a state of ideal weightlessness.*

In figure 2.6 B, a variety of the case in figure 2.6 A has been sketched. The person with the box has been submerged in water and may be regarded as a diver on the bottom of a pool. The density of a person is almost the same as that of water. The diver will therefore not cause a big pressure against the bottom (F'_3 and F'_4 will be much less than F_3 and F_4) and his arm is raised up through the buoyancy of the water (F_2 reduced). Accordingly, the diver is in a way approaching a state of weightlessness. *Astronauts are therefore often trained by carrying out tasks in water.*

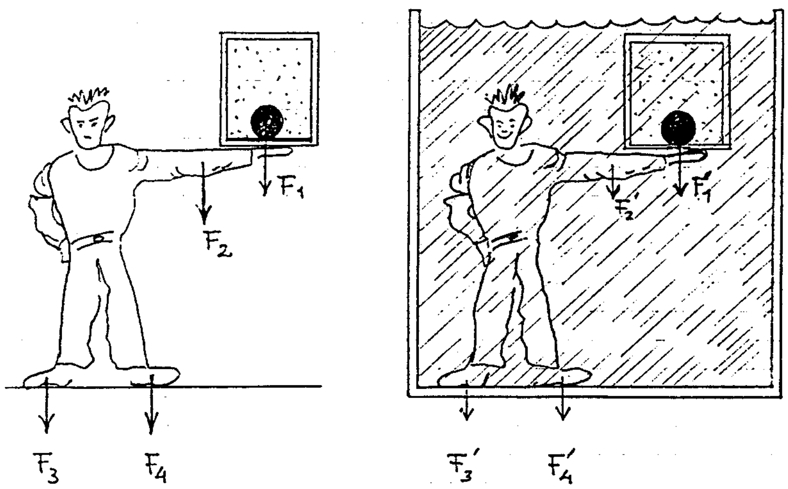


Figure 2.6. Partial simulation of microgravity conditions.

In 2.6.A, some of forces created by the gravity and acting on a person standing on the ground are illustrated. F_1 shows the force acting on the sphere in the container, the force being dependent on the density differences between sphere and liquid, cf. Figure 2.2. The force F_2 depends on the total mass of the container and the arm and has to be compensated by muscle forces. Forces acting on the floor are represented by F_3 and F_4. (No counter forces are shown). In 2.6.B the person and the container are placed in the water in a water tank experiment. The buoyancy acts to decrease the magnitude of several of the forces: F_2, F_3 and F_4 are now smaller. Dependent on the density of the liquid one can even imagine the forces to become zero. The person will have less problems to carry the container due to the buoyancy. But the pressure of the heavy sphere in the container will still have the same magnitude since it is determined by the density difference between the sphere and the liquid and it has not changed (the force F_1' is the same).

On the contrary, *in free fall the forces will be zero and the corresponding pressures will be zero*

But one should be careful: the iron ball in the box acts with the same force $F_1 = F_1$' against the bottom of the box in both cases! This is so because the force is proportional to the difference between the density of the iron ball and that of the surrounding liquid, both of which are unchanged. The pressure against the bottom of the box will therefore be the same below as above the water surface! In this case we could obviously not manage to compensate the force and pressure by submerging the astronaut and his equipment in water, and we have consequently no weightlessness in the way we may have in a spacecraft! (In Spacelab F_1' would also become negligible).

Often differences between 1*g* situations and weightlessness may be traced back to some of the effects and figures we have just discussed. Two observations:

a. During 1*g* situations the human skeleton is exposed to a load, which is the body weight exerting a pressure on the individual parts of the skeleton. If we are lying horizontally, this picture will obviously change; the pressure will become smaller. The *regulation of the calcium* balance of the skeleton is a complicated process, but a great part of the situation can be summed up by saying that the load on the skeleton under normal circumstances will control the quantity of calcium in the different parts of the skeleton. If the load is *increasing* the controlling system will act in such a way that more calcium is stored in the bone. This means that the skeleton becomes harder and more able to resist the increasing load.

Correspondingly: If the load *decreases* (if we are in bed for a long time - patient in hospital!), the skeleton will loose calcium via blood, faeces and urine. The result will be a decalcification of the skeleton. This may for example be measured by the stiffness of the bones (cf. Figure 2.3).

Also in weightlessness the pressure on the parts of the astronaut's skeleton becomes smaller, and decalcification takes place. This gives rise to concern for longer stays in space. Pictures from the return of cosmonauts to the earth after more than a year in weightlessness show that they cannot stand upright by themselves immediately after coming into the 'normal' 1 *g* conditions. The body processes must be given enough time to reconstitute the skeleton. This research area of bone calcification, regulation of the calcium content etc. is one of the most important problems in space medicine. It has of course a close connection to problems around *osteoporosis.*

b. In every day life our body can not escape from the effects by gravity: As seen in the mirror also features of the human face is changed when orientation with respect to gravity changes. When in bed the body redistribute the body fluids more evenly and that is why your face is more "swollen" when you stand up in the morning, looking in the mirror. Correspondingly: In microgravity the blood is more smoothly distributed in the body than under 1*g* conditions. Again: The upper parts of the body then get relatively more of the blood volume, and the lower extremities get less compared to the situation on earth.

2.4 Mixing and stirring in fluids due to variations in density. Convection.

If we have got a liquid with different densities in different parts of it the situation will lead to transport and stirring in the liquid under normal 1 g circumstances (of course, ΑΡΧΙΜΗΔΗΣ!). According to section 2.3 different densities lead to sedimentation or buoyancy, in turn leading to the stirring and the mixing. Stirring due to differences in salt concentrations can, e.g., happen in the sea and in a river mouth.

On a smaller scale we may think of an everyday example: If we are holding a bit of sugar in coffee at a certain distance above the bottom of the cup, the sugar will dissolve into the liquid and create a dense (and heavy) solution of sugar that will sediment. When growing crystals of different compounds for structural experiments, this may cause problems. Figure 2.7 shows how a heavy solution sinks from a crystal, slowly dissolving in the liquid. An optical method of recording differences in concentrations as "contour line map" (with iso-concentration lines) has been used (Schlieren-photographs).

Of course such stirring processes, driven by the force of gravity, will not happen at all in absolute free fall and to a very much reduced extent in microgravity. *Convection* is a bulk movement, and takes place because of local gradients in a fluid. Also *temperature gradients* can cause convection For instance, since a hot liquid is often less heavy than a cold one and therefore will rise upwards, a production of heat at one place in the liquid may lead to

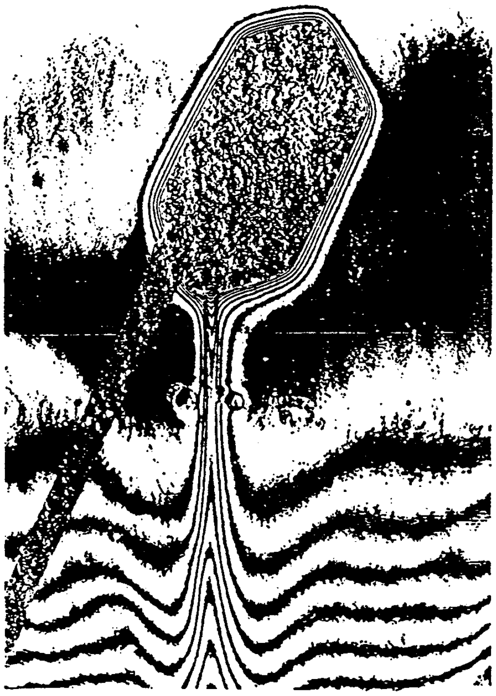


Figure 2.7. Crystal dissolving in a liquid. By a special photography technique the density variations in the liquid are represented by the alternating black and white stripes. The crystal (of sodium chlorite) is slowly dissolving in the liquid and under the influence of gravity, the liquid volumes with higher salt concentration (and accordingly, higher density) are moving towards the bottom of the figure

convection. Convection in air masses will also occur due to local heating, for instance above a piece of land.

Such convection, basically due to gravity, does not take place in weightlessness.

In general one may say that physical, chemical and biological experiments in weightlessness quite often aim at examining what happens in the absence of bulk movements in a fluid.

Some relevant scientific and technological examples and areas should be mentioned here.

a. The diffusion process.

Diffusion is basically a transport process depending on the random heat movements of molecules, not on the stirring of liquids and not on convection. It is driven by a *concentration gradient.*

The diffusion of molecules occurs from a region of high concentration towards a region with low concentration. The movement of individual molecules when no gradients are present is characterized by a random movement, generated by heat. Superimposed on these random movements the diffusion will occur and the net transport will be in the direction of the negative gradient (i.e. towards regions with lower concentration). The velocity of the diffusing molecules in a liquid is determined by the temperature, the size and shape of the molecules, the viscosity of the liquid and so on. The velocities can be calculated (as we will see later) when one knows the *diffusion constant*. This constant is important for solutions, melting alloys, molecules in a metal etc.

The general differential equation for diffusion in one dimension is seen below, the factor D is called the diffusion constant (c represents the concentration of a substance at position x; t denotes time):

$$\frac{\partial c}{\partial t} = D \cdot \frac{\partial^2 c}{\partial x^2}$$

In contrast to convection and stirring of a liquid, diffusion itself is not connected with bulk transport of fluid elements.

Measurements of transport velocities of substances give the opportunity to calculate their diffusion constants in different media. But *in order to get exact measurements, the transport must be result from diffusion only, and not be disturbed by some kind of convection in the liquid*. Such stable conditions, free from mixing, convection etc are, however, extremely difficult to achieve in a liquid container in a laboratory under $1g_0$ conditions. Free fall conditions, where stirring and movement of the liquid can be avoided, are therefore a possibility to achieve considerably better conditions for exact determinations of diffusion constants. In some space experiments, new and considerably more exact values of diffusion constants (with a deviation of up to about 20% from the $1g_0$ values) have also been achieved.

b. Crystal growing.

The study of atomic or molecular structure of crystals and alloys is a key theme in great parts of modern physics and chemistry, generally within the *material sciences*. The exact three dimensional structure of materials is of great scientific and industrial importance and much effort is devoted to achieve precise data.

The production of crystals and alloys is often accompanied by crystal defects as they are produced from solutions/melts during 1g conditions. Among other things, the defects depend on the liquid stirring and liquid transport taking place around the crystals when they are growing. The crystal defects make the analysis of the three dimensional structures impossible or more difficult.

Also the *size* of the crystal depends on the amount of stirring in the liquid. The crystal size is an important parameter since the determination of structure can be performed with a higher degree of precision when the crystal to be studied is big and perfectly built. The crystal structure is most often determined by the use of *x-rays* or *neutron rays*. The diffraction pattern created by the crystal structures when they are placed in the beams is used to calculate the crystals structures. Crystals of the size of approximately 0.1 mm are mostly preferred for x-ray analysis. In radiation with neutrons the crystals have to be about ten times bigger.

In microgravity the hardening of substances, alloys etc. will occur without convection as we have seen. Crystals and materials of extreme homogeneity, size and precision may then be achieved. An example of growing a gallium doped Ge-crystal appears in Figure 2.8. Equally spaced time intervals are indicated in the figure. In the lower part of the figure the crystal is grown under the influence of 1g force, and irregularities in the structure may easily be seen. On the other hand, in the upper part of the figure the growth has taken place in microgravity, and the structure here shows much less defects and only the indicated time intervals may be seen.

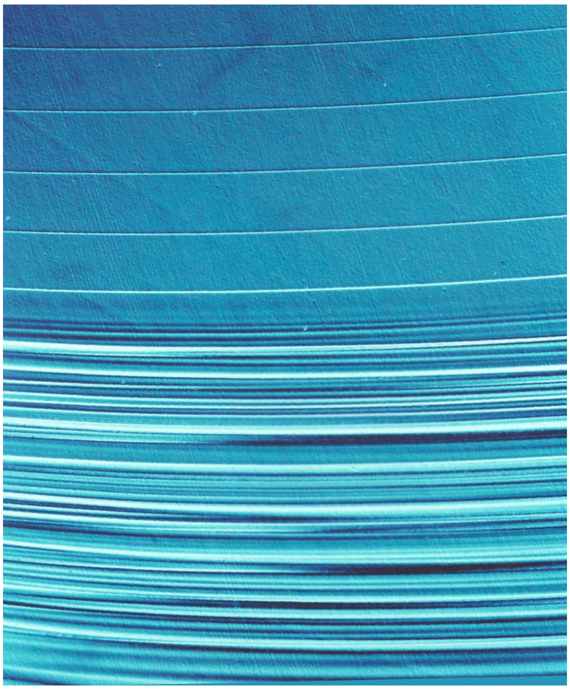
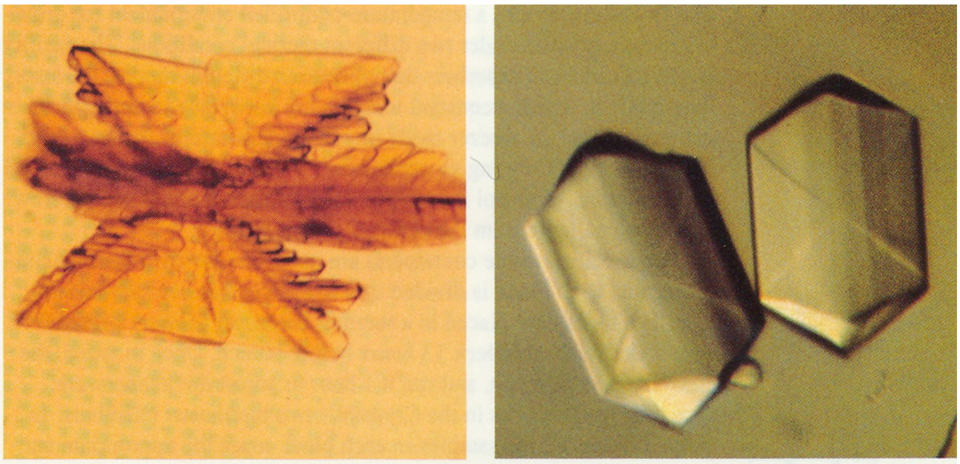


Figure 2.8. Gallium doped germanium crystal produced under 1 g and under microgravity conditions. The crystal surfaces show traces from the production process. The lowermost part was manufactured on the Earth. The growth continued in a rocket (an ESA TEXUS rocket) in microgravity, uppermost part of figure. The last part produces much cleaner and perfect structures. The speed of the crystal growth are indicated by the regular markings, the distance between markings indicate equal time intervals.

Growing crystals and materials (for subsequent analysis – which can be carried out on earth) has become an important area for microgravity experiments. The key point is the absence of stirring and convection in the liquid and the crystal growth is basically due to unperturbed van der Waal attraction between molecules, giving perfect layers that deposit on the crystal “surfaces”. At several occasions it has been possible to make considerably better products in space than on earth. Some examples of organic crystals of interest in space research experiments are shown in Figure 2.9 and 2.10. Figure 2.10 shows the difference between crystals of the protein isocitrate lyase grown on earth and in space.

Figure 2.9. Crystals of bacterial rhodopsin.
This molecule is a cell membrane protein that in some organisms transform light energy into electrical voltages across the membrane. In such organisms, archaebacteria, the bacterial rhodopsin provides an important system for our understanding of the how mechanisms responsible for light induced molecular transport across membranes were created during evolution. The rhodopsin mechanisms are also essential for our understanding of the first steps towards photosynthetic mechanisms.

The mechanism by which rhodopsin works are to be understood by its three dimensional structure – once again experiments in microgravity will hopefully provide relevant clues.



Some protein crystals grown on the ground have odd shapes that interfere with analysis. For example, crystals of isocitrate lyase, a plant enzyme targeted by fungicides, often have tree-like growths, called dendrites (a). On STS-26 (September 1988), the first distinct prisms of isocitrate lyase (b) were grown in space; over 25 crystals were produced on this mission.

Figure 2.10. Crystals grown on Earth and in Space.
Isocitratelyase is an enzyme, i.e. a protein, of interest in studies of fungicides. When the crystals are produced under 1 g conditions, left figure, the result is a dendrite like structure. Dendrites are not suitable for precise structural studies. Larger crystals, suitable for analysis were achieved in space.

Different techniques have been used in order to obtain suitable growing conditions in space research. One method is to get successively increased concentration in a liquid by evaporation of liquid, and subsequent crystallisation and growth of crystals.

Especially when it comes to *proteins*, organic molecules that play a key role in biological processes for example as enzymes, there are great expectations linked to the experiments in microgravity. Several experiments have been carried out in order to achieve larger units of proteins that may be tested to achieve the protein structure. Fundamental proteins like the central unit in photosynthesis (PS II) has been crystallized in this manner and contributes to our understanding of one of the most fundamental processes in life.

In 2009 Ada E. Yonath got the Nobel prize in chemistry for her pioneering X-ray crystallography work on ribosomes (extended to extremely low temperatures). Ribosomes are responsible for the translation of the genetic code and necessary in the protein production. While they are the only organelles in living cells to have been crystallised, most of the Earth-grown crystals are very thin and crack upon handling, causing severe difficulties in data collection and evaluation.

Experiments in Space with Yonath as principal investigator (e.g. in the Advanced Protein Crystallization Facility in Spacelab), however, delivered crystals of better proportion than those grown on earth, with more isotropic shape and not as brittle and fragile.

Figure 2:11. Ada Yonath receives the Nobel Prize in chemistry in 2009 (awarded jointly to Venkatraman Ramakrishnan, Thomas A. Steitz and Ada E. Yonath *"for studies of the structure and function of the ribosome"*). Studies of space grown crystals were important in her research. (Photo: Nobel Prize ceremony photo).

An inorganic structure of considerable interest for producing x-ray detectors etc., is *mercury-iodide*. It is an interesting goal to obtain large crystals of this substance, and several methods for making them in the space have been tried, one depicted in figure 2.12.

Figure 2.12. Growth of mercury iodide crystals.
Mercury iodide crystals are of commercial interest and are used, e.g., as sensor units to detect X-rays. In one method used in weightlessness crystal growth is carried out by allowing evaporation at higher temperature of a (fairly low quality) material onto growing (pure) iodide crystals. Slow and controlled growth is then possible and the faces of the crystal are slowly covered by new atomic layers (”Vapour Crystal Growth System”).

The figure to the left shows a crystal under production (some reflexes in the upper right part of the figure). Crystals bigger than cm could be grown in space.

c. Combustion process. Convection around an open flame.

A candle burning on earth has a flame with a characteristic shape and colour. How will this flame look like in microgravity?

As a starting point we should remember that for the combustion to be possible at all, three requirements need to be met: A *flammable material* must be present, the *temperature* must be high enough and *oxygen* must be supplied to the place of fire. Under 1 g_n the combustion would then take place in a normal way and the flame achieves its shape by heating up surrounding air which, due to convection, is transported upwards. This allows cold air to flow into the wick area and supply the combustion with oxygen. *The air flow causes the characteristic shape of the flame.*

What would happen if the burning candle were placed on a centrifuge giving a larger value of g, perhaps 2 g_n?

If the burning candle is placed on a centrifuge and exposed to a force of 2 g_n, the convection process will be somewhat changed. But the principle forming the basis of the combustion will still be the same, and the flame will more or less keep its shape - the only difference is that it will become somewhat sharper and might be higher/longer due to the air more intense air movement. What will happen in free fall?

The free fall experiment has been carried out at strictly controlled conditions and figure 2.13 gives a picture of the resulting flames.

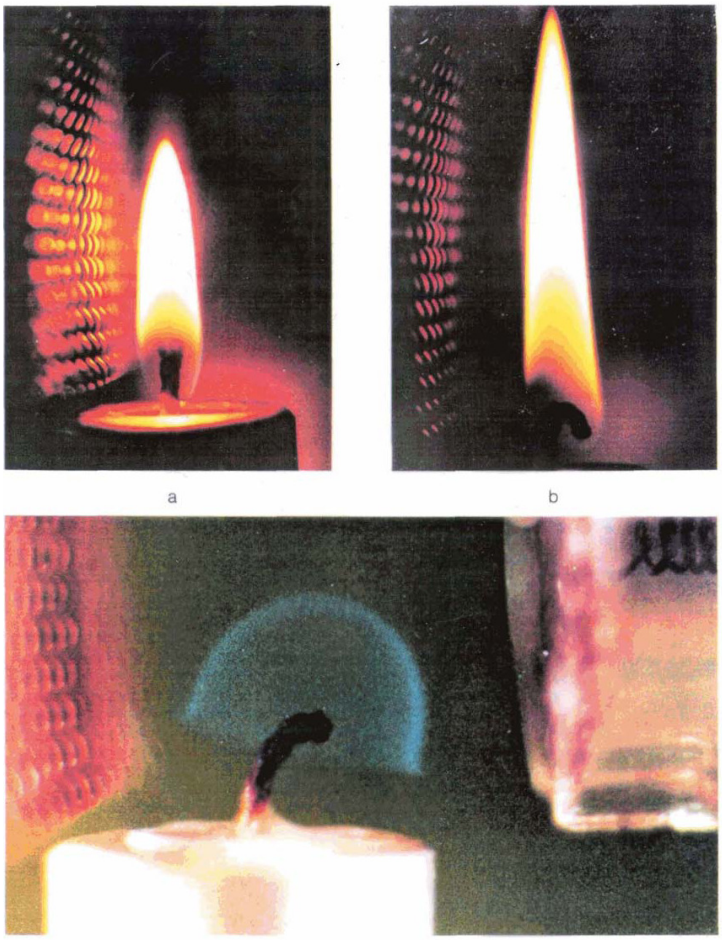


Figure 2.13. Burning flame studied in parabolic flight.

In figure 2.13.a., the candle is burning under 1 g conditions. Figure 2.13.b shows a picture of the flame under acceleration of the air plane in the parabolic flight, the g-acceleration is about twice as big as in figure 2.13. a (cf. also Figure 1.7). Form of flame determined by air convection.

Figure 2.13.c shows the flame in microgravity, the camera being closer to the wick. A bluish, almost half spherical burning zone has now replaced the flame. The colour change indicates that the temperature is changed; the form of the burning flame is explained by assuming that oxygen is now transported into the zone from the surrounding air by other processes than convection. The convection is negligible in microgravity. The new transport process of importance is diffusion.

d. Spaghetti cooking.

Imagine a pan with spaghetti placed on a heating plate. At 1 g_n -conditions the water will become heated by the plate, there will be some convection and water vapour bubbles will be created. Due to the buoyancy the bubbles will move upwards and because of the general movement in the water the content of the casserole will more or less get the same temperature. Finally the water starts to boil and the spaghetti is getting heated in a regular manner.

In free fall there will be no convection or buoyancy and subsequent stirring. Consequently, the water close to the plate will become hot and the spaghetti in the lower parts of the pan will be heated up. Also in this case water vapour bubbles will be created, but they will not move upwards - on the contrary, a huge combined bubble will be created just above the heat source. Since no stirring is present, the spaghetti in the upper part will remain hard!

e. Example of recent report

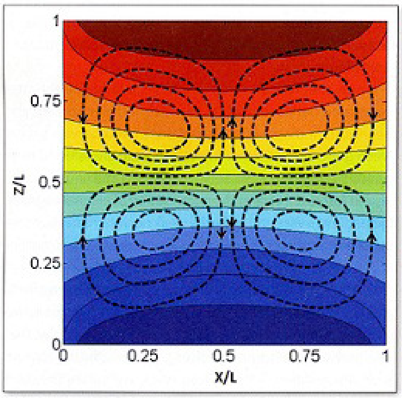
Lots of free fall experiments are performed on the ISS. An illustration can be given below, where an experiment on thermo-induced diffusion has been performed in weightlessness in 2014. How do a temperature gradients influence diffusion without causing bulk liquid movements (convection)?

Highlights from European journals

LIQUID PHYSICS

Thermodiffusion in weightlessness

Zero gravity experiments on the International Space Station shed some light on thermodiffusion effects, relevant to the oil and gas industry and global warming prevention processes



▲ Flow pattern 2 minutes after the start of vibrations. Credit: Y. Gaponenko *et al.*

Thermodiffusion, also called the Soret effect, is a mechanism by which an imposed temperature difference establishes a concentration difference within a mixture. Two recent studies provide a better understanding of such effects. They build on recent experimental results from the IVIDIL—Influence Vibration on Diffusion in Liquids—research project performed on the International Space Station under microgravity to avoid motion in the liquids.

In the first study, using a mathematical model the authors set out to identify how vibrations applied to a binary liquid mixture change the temperature and concentration fields over a long time scale. Their findings—if extended to ternary mixtures—have implications for models used to evaluate the economic value of oil reservoirs.

The second paper uses numerical models to study the establishment of the concentration field near the critical region, where diffusion strongly diminishes. Surprisingly, the authors demonstrate that the component separation through the Soret effect is saturated and not infinite, and is reached surprisingly rapidly. The findings of this study may help determine whether the Soret effect could lead to a very large accumulation of sulfur dioxide and hydrogen sulphide capable of creating a leak in the cap-rock of a reservoir, during the process of capturing CO_2 and reinjecting it in supercritical state in such a reservoir. ■

- **Y. Gaponenko, A. Mialdun** and **V. Shevtsova**, 'Experimental and numerical analysis of mass transfer in a binary mixture with Soret effect in the presence of weak convection', *Eur. Phys. J. E* **37**, 90 (2014)
- **J.C. Legros, Yu. Gaponenko, T. Lyubimova** and **V. Shevtsova**, 'Soret separation in a binary liquid mixture near its critical temperature', *Eur. Phys. J. E* **37**, 89 (2014)

2.5 Surface-phenomena, capillary forces. Marangoni-forces. Examples.

Surface tension plays an important role when two media, e.g. water and air, come in contact with each other. Since the molecules at the surface are not surrounded by the same type of molecules in every direction, the molecular forces at the surface become special with respect to the situation in the bulk liquid. At the surface, the molecular forces directed "inwards" achieve a net component that gives rise to the so-called *surface tension*.

Surface tension controls, among other things, the *shape of bubbles and drops*, and often interacts with the force of gravity to determine their final shape. The surface conditions are often given by an equilibrium situation between surface tensions and the force of gravity.

The influence of surface tension will be proportionally bigger with decreasing force of gravity, and thus with a lower value of *g*. Bubbles and drops will in this case become significantly larger than at 1g conditions. A drop of water on a glass plate will for instance "flow out" and might form a layer on the glass plate at 1g. But its precise form in free fall will be determined by the molecular forces at the contact points with the glass plate and the surface forces - the gravity will play no role.

> **Example:** Experiments involving gases dissolved in fluids have been performed in microgravity. A sequence of pictures shows this in figure 2.4. The small gas bubbles created join into larger bubbles due to the influence of surface tensions in weightlessness. They stay in the liquid, combine more and more and squeeze the liquid out of the container.
>
> Obviously, knowing how liquids behave in weightlessness is important for controlling the behaviour of the liquid fuel, injection processes, combustion processes and so on in spacecrafts and spacecraft motors.

In microgravity the form of a water drop will be exclusively determined by the surface tension. Accordingly it will have a spherical form. The radius of water bubbles “floating around” in weightlessness can in principle be very big – such water “droplets” with a radius of more than 5 cm can easily be created!

*

Also *capillary forces* represent an example of how molecular forces are able to manifest themselves by contact between different media. Figure 2.14 is an illustration of a glass tube containing a column of water. If the tube and the liquid are kept at 1g conditions, the surface forces will act on the rim of the interface between liquid, glass and air. The magnitude of the forces depends strongly on the kind of liquid and the properties of the glass surface. The upward acting force is given by the product of the length of the contact line between liquid and glass tube and the surface tension.

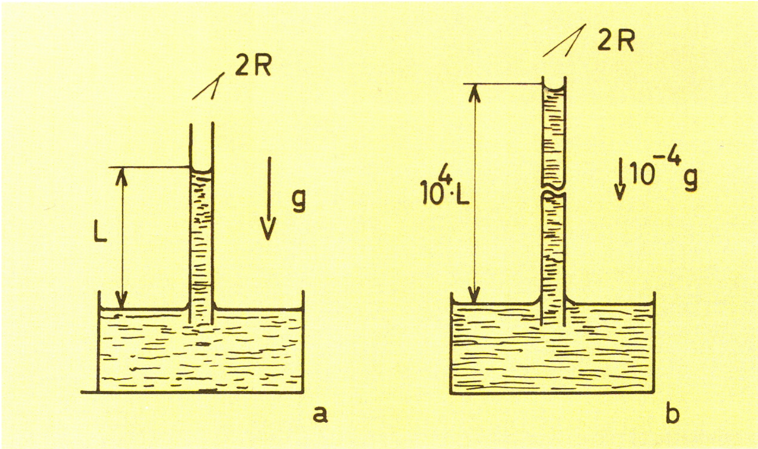


Figure 2.14. Capillary forces.
In 2.14.a the capillary forces acts under 1 g_n conditions and the liquid is elevated to a certain height L. The same capillary (diameter 2R) is used in the experiment in figure 2.14.b. to the right. Since the g-value is then 10 000 times lower, the capillary forces will raise the liquid 10 000 times higher.
In microgravity, liquids in porous structures will behave differently than under 1 g_n conditions. Capillary forces, surface tensions etc will have proportionally more influence on their behaviour. This can be used to achieve more "pure" experimental conditions than on the earth.

The force of gravity acting on the total mass of the liquid is indicated by the arrow directed downwards. The magnitude of this force will be $\rho h g \cdot \square r^2$ with conventional notations. It evident that the height of the liquid within the capillary is inversely proportional to g, which means that the liquid pillar will become 10 000 times higher if the capillary is under the conditions of 10^{-4} g_n (which can be the case if one has perturbations during the flight)!

For liquids in porous systems (e.g. water in soil), water transported in trees, capillary transport etc., the relationship between surface tension and g-value plays a rather important role when it comes to transport. Much of physics and physiology connected to capillary phenomena should therefore be expected to be quite different in weightlessness.

Surface waves.
Under normal circumstances, waves created on a surface of a liquid are counteracted by two effects:

- The force of gravity acts as to decrease the wave height, and
- The surface tension of the liquid will decrease the surface area, in turn decreasing the height of the waves.

Characteristic wave lengths etc. under 1 g_n conditions are determined by both of these effects.

In microgravity, however, the situation is changed, and waves on the surface of a liquid (e.g. on a liquid ball that may be imagined "floating around" in Spacelab) are solely determined by the surface forces and the surface tension.

Marangoni-forces.

Forces with a direction *parallel to the surface of the liquid* are called *Marangoni*-forces. These forces may for instance arise if the different parts of the surface have different surface tension (the liquid flows e.g. along a gas-liquid interface from areas having low surface tension to areas having higher surface tension).

On earth, studies of Marangoni-forces are difficult to perform. This is so, since they are seriously disturbed by forces and effects generated by gravity, e.g. convection in liquids. Space experiments have therefore been a requirement for such studies and the starting point for the wide interest that the studies of Marangoni-effects have got in modern liquid physics.

2.6 General transport processes.

A short section about transport processes will be given below. Generally speaking, transport of a substance takes place in a system if gradients in the so-called *electrochemical potential* are present. This is formally similar to the situation in an electrical system, where charges are transported depending on an electrical potential difference U in the system. The use of the concept of electrochemical potential is just as practical to work with as the notion electrical potential U, and includes, as will be seen below, in reality also transport of charges.

The electrochemical potential, usually denoted μ, can be defined in such a way that it comprises terms covering

* bulk transport
* electron (charge) transport
* diffusion

etc.

The gradient of μ will determine whether a transport is going to take place. We therefore calculate grad (μ) and different terms can be specified as follows (other relevant terms may be added if the system has special properties):

$$\mathrm{grad}(\mu) = \overline{V} \cdot \mathrm{grad}(P)$$

$$\mathrm{grad}(\mu) = zF \cdot \mathrm{grad}(U) \tag{13}$$

$$\mathrm{grad}(\mu) = RT\frac{1}{c}\mathrm{grad}(c)$$

For a given system one or several of these terms can be of interest.

In general the flux of a substance or transport of a substance, is defined in the following way:

$$\mathrm{Flux} = -(\mathrm{mobility}) \times c \times \mathrm{grad}(\mu) \tag{14}$$

The abbreviations introduced in the formulae are the following ones:

- μ = The electrochemical potential of the substance
- c = The concentration of the substance in the solution
- $\overline{V}$ = The (partial) molar volume of the substance
- P = Hydrostatic pressure
- z = The number of charges pr. ion (in the case of a charged particle)
- F = Faraday's constant
- U = The electrical potential
- R = The Gas Constant

We observe that parts of the first term (grad P) can disappear in weightlessness, e.g. if it contains pressure differences due to gravitational forces, while the others will be the same in weightlessness (free fall).

3. BALANCE SYSTEMS AND SEDIMENTATION AT DIFFERENT *g*-VALUES.

3.1 Balance system for detecting force vectors. Mass perception.

Balance systems are developed in both multi- and single cellular organisms, both in man, animals and plants. The human balance system is rather complicated, and the brain works with several kind of input signals. This is because it is essential to us to orientate ourselves in relation to the vertical, which is our chosen reference direction, and redundancy therefore exists in the overall balance system. The concepts and notions of «up», «down» etc. are directly connected to our balance system. On a centrifuge we relate the concepts of up and down to the combined vector of the gravitational and the centripetal forces.

A balance system also acts as a control system, a regulatory system, where a deviation of the body from the reference direction is understood as an error signal. This error signal - the unbalance with respect to the vertical - is then treated in physiological processes which finally lead to a compensation of the unbalance or the error signal. In Man one may say that there exist three kinds of input signals that are of great importance for the overall balance system:

a. Electrical signals from the *vestibular* organ, situated in the inner ear.

b. Signals from the eyes that give information about positions and movements of the body in relation to the visual frame of references of the surroundings.

c. Signals from the muscular-skeleton system (*proprioceptive* system; «muscle tonus»). Under normal conditions these signals naturally take part in the compensational movements of the body.

The signals from the three input sources are integrated in the brain, and the brain may adjust to the lack of one or two of the signals.

The *vestibular organ*, in the inner parts of our ear, records several important parameters. It records accelerations around the three perpendicular axes, i.e. x, y, and z axes. The *semi-circular canals* in the vestibular organ act as a kind of pipe filled with a fluid. When the head is rotated around one of the three axes the movement of the fluid in the canals will initially be slower than the movements of canals (and our head). The fluid in the canals will therefore move relative to the canals. This relative movement is recorded by a stimulation of nerve endings at the inner surface of the canals, in turn used to record the accelerations and the movement of the head around the three axes.

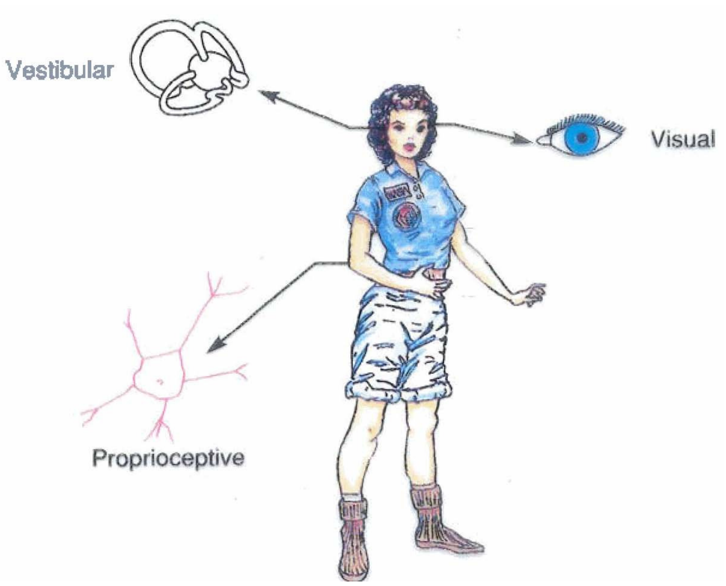


Figure 3.1 The balance system of mammals is bases on signals from the vestibular organ, the eye and the so-called *proprioceptive* system (the muscle – skeleton that sends information about the positions and weight of arms, legs etc in the body. Information is fed to the CNS, central nervous system. Control of position then occurs via the nerves and the regulation of muscles in the body.

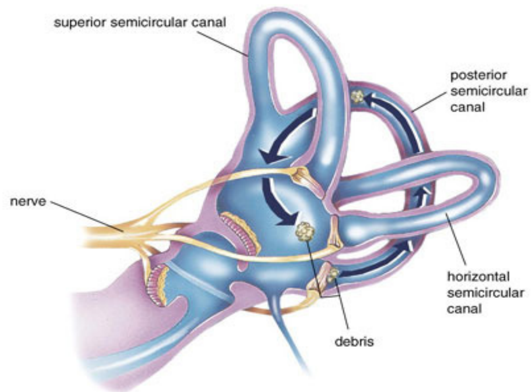


Figure 3.2 The ‘inner ear’ organ. Three semi-circular canals contain fluid that move due to accelerations of the head around the x-, y- or z-axis. The middle part of the picture shows a membrane that is loaded with ‘heavy’ particles, otoliths, exerting stretch on nerves that can send positional information to the brain. Together the organ constitutes the sensory system necessary for controlling the balance in many mammals.

The vestibular organ also acts as a *position detecting organ*, in the sense that an angular deviation of the head (body) from the plumb line can be detected. It can thus detect what is "up" and what is "down". The basic physical principle of the sensor is *mass-perception.* This means that the sensor system is detecting the position or changes in the position of certain masses in the organ. In principle, *this part of the vestibular organ is similar to most of the biological sensory organs in plants and animals that sense direction and size of the gravitational force.*

The detection of the mass position takes place by detecting the pressure on a particular place on the bottom part of a cell or an organ. If the position of the organ is changed (let us say that it is inclined with respect to gravity), the position of the mass will also change, and the pressure will be transferred to a new position. The pressure can activate cellular membranes of the organ, and electrical signals can be generated that are related to the position of the pressure. Through a kind of neural network the electrical signals reach the central nervous system of the brain.

Shortly summarised: *the movement or sedimentation of a particle (or particles) in an organ is the key process of the mass perception in the balance systems.*

Basically, balance systems in widely different organisms are based on the same principle. An example from a unicellular alga, *Chara*, is shown in figure 3.3. Usually, small particles are seen to be situated in the very end of the growing *rhizoid* structure of this alga and indicate where the growth will take place. The rhizoid (one cell!) grows downwards in the direction of the gravity.

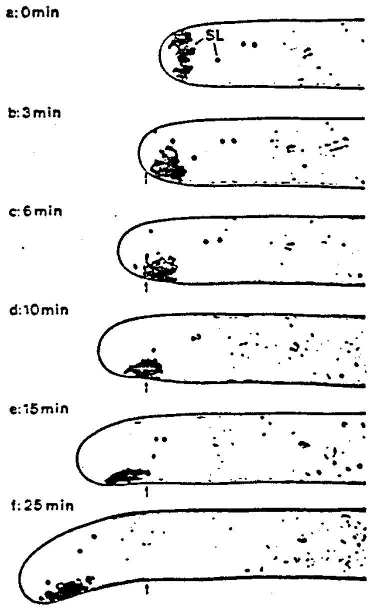


Figure 3.3. A series of photos of some parts of a unicellular algae (*Chara*) and its gravity induced curvature. The system was put into horizontal position at time zero, and the statoliths, SL, were then distributed in the tip of the organ. After 3 min the statoliths had sedimented and after 6 min they seemed to be in contact with the bottom of the organ.
The downward growth in the direction of gravity starts after about 15 min. The arrows indicate a fixed point of the organ, and its relative position demonstrates that the reaction is a growth reaction (the distance from the tip is increasing with time).

If the rhizoid is placed in a horizontal direction as in the upper part of the figure, the particles will, under the influence of gravity, become redistributed. They will then exert a pressure on a new part of the cell - the "under" side of it and cause the growth to be slower on the under side than on the upper side. The rhizoid will, therefore, change its growth direction and will not grow horizontally, but will deviate downwards. In this way it will compensate the error signal (90 degrees with respect to the plumb line!) registered by the balance system. Finally, the error signal is fully compensated and the rhizoid has made a 90 degrees turn and will grow "downwards" again. The particles have then been redistributed in the cell but will finally be at the tip of the rhizoid, pointing downwards. We see that the cell uses the distribution and the position of heavy particles as the basic principle for its sensory system. The small particles in the *Chara* algae are made of barium sulphate.

The significance of weightlessness and experiments in space in this context:

- *Weightlessness puts the mass perception out of action.* Sedimentation and gravity driven movements of heavy particles will not occur in free fall.

- *The weightlessness provides an extraordinary tool for studying the properties of the balance systems.* One can also study balance organs in the acceleration region 0 g_n to 1 g_n by placing the organism on a slowly rotating centrifuge in a satellite in free fall. The organism will then be exposed to acceleration forces *only* due to the centrifugation, and one can, e.g., expose it for 0.1 g_n!

3.2 Basal processes when stimulating balance systems. Sedimentation.

The heavy particles as mentioned in the previous section have got special names. In the vestibular organ of man and animals they are called *otolithes*, which comes from *otho* - ear and *lithos* - stone. In the world of plants the heavy particles are called *statolithes* (from *statos*

– stationary).

For simplicity, we will consider the cell fluid to have homogenous and well defined character. This is not at all trivial and is in principle wrong - for instance is the "viscosity of the cell fluid” not a well defined property. Anyway, this is the simplest method when trying to understand some of the problems concerning the biophysical properties of a balance system. We will simultaneously understand the argumentation behind some flight experiments in space.

For a statolith sedimenting in a cell at 1g condition, schematically in figure 3.4, we can calculate the downward force due to gravity and the upward force due to buoyancy etc.

The net downwards directed force becomes

$$F_{\text{down}} = \Delta m \cdot g$$

The physicist Stokes discussed the force, directed upwards, when the particle is moving in fluid. He derived a formula for this force applied on a spherically shaped body, when the sedimentation velocity is not too high. This formula is given as:

$$F_{up} = -6\pi R\eta \frac{dx}{dt} \tag{15}$$

The x-direction is then defined to be in the direction of the force of gravity. The notions are the conventional ones: *R* is the radius of the sphere, η is the viscosity of the fluid and dx/dt is the velocity of the sphere.

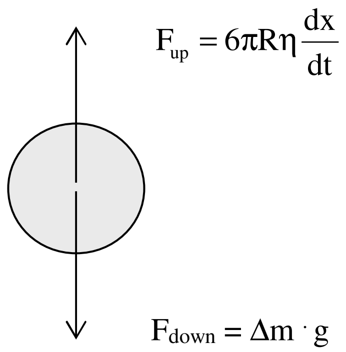


Figure 3.4. Forces on a sphere sedimenting in a liquid.
Gravity = 1 g. The downward directed force on the sphere is dependent on the difference in density between the sphere and the surrounding medium. The upward directed force is due to the drag and is dependent on the sedimentation speed, the radius etc. When the sphere is released in the liquid, its downward speed will increase until F_{down} equals F_{up}. Then the net force is zero and the sedimentation velocity will be constant.

The sedimentation process starts with zero velocity when we release the sphere. The simplest situation we can study is the one we get when considering the velocity of the sphere after the sedimentation has continued for a while. Just as a ball in syrup reaches its terminal velocity very fast, we will in our sedimentation process get an equilibrium situation very soon since the viscosity of the cell fluid is high. The sphere will, therefore, very soon sediment with a final speed, denoted $(dx/dt)_{end} = v_{end}$ This equilibrium situation can be calculated by setting $F_{down} = F_{up}$:

$$\Delta m \cdot g = 6\pi R\eta \, v_{end} \tag{16}$$

$$v_{end} = K \cdot g \tag{17}$$

where

$$K = \frac{\Delta m}{6\pi R\eta}$$

The above formula, giving the expression for the terminal velocity of the statolith, is commonly used in the literature. To calculate v_{end}, data from the literature must be used and it turns out that there are great uncertainties also in the magnitudes of the parameters. Some approximate values are the following:

$\Delta\rho = 0{,}3\ g/cm^3$
$R = 1\ \mu m$
$\eta = 0{,}02\ Ns/m^2$

3.3 Threshold effects in the balance system under stimulation.

An important task for physiologists and biophysicists is to study the *sensitivity* and possible *sensitivity thresholds* of the sensing organs. As for the eye, for instance, we understand that an absolute requirement is that a photon must be absorbed by a molecule in the retina if the eye system should react at all. Correspondingly, in any sensor system enough energy must be transferred to the sensor for a reaction to take place.

Returning to sedimentation processes, we understand that the potential energy is changed during the process. Potential energy is lost while kinetic energy is gained.

For the cell to be able to detect the sedimentation, we can imagine that in our system *the energy change must at least exceed the level of the thermal noise*. This means that the loss in potential energy must at least be greater than kT, where k is Boltzmann's constant and T is the temperature. kT represent the thermal noise present in the fluid of the cell in which the sedimentation is considered. We then get the following requirement for detection (under 1g conditions):

$$\Delta mg \cdot \Delta x \geq kT \tag{18}$$

Δx is the minimum distance the statolith has to sediment if the process should be detected by any sensor in the cell.

However, if we assume that Stokes' law applies to the situation we can now advance one step further on. If we assume that we can approximate the sedimentation velocity with a certain distance □x, divided with the corresponding sedimentation time Δt, we can write the terminal velocity as

$$\nu_{end} = \frac{\Delta x}{\Delta t} \qquad (18A)$$

Assuming that the minimal distance □x can be equated in the two equations (16) and (18A), we get the following expression where the shortest sedimentation time, Δt, is included:

$$\Delta m \cdot g = 6\pi R \eta \frac{\Delta x}{\Delta t} \qquad (19)$$

How should we interpret *Δ*t? The easiest is to say that *Δt* represents the minimum time the sedimentation process must go on, according to our mathematics, in order to overcome the thermal threshold). This again becomes the shortest time necessary to detect the sedimentation. With use of formula (19) we may now get a more explicit expression for Δt:

$$\Delta t = \frac{6\pi R \eta \Delta x}{\Delta mg} \geq \frac{kT 6\pi R \eta}{(\Delta mg)^2} \qquad (20)$$

If we use the parameter values given on page 47, we get a minimum time, Δt_{min}, of about 25 seconds! Even though the parameter values were rather uncertain, it becomes a fairly short time. Is this the threshold value necessary to detect the deviation in the equilibrium system of the cell at 1 g_n?

A schematic picture of a plant cell is shown in figure 3.5. The complicated schematic picture is based on modern microscopy and also on many results from space experiments. There is not only *one* statolith in each cell. If we in our sedimentation process have N particles, the shortest sedimentation-distance necessary to overcome the thermal noise might become correspondingly less and Δt ≈ 25/N seconds, i.e., a few seconds.

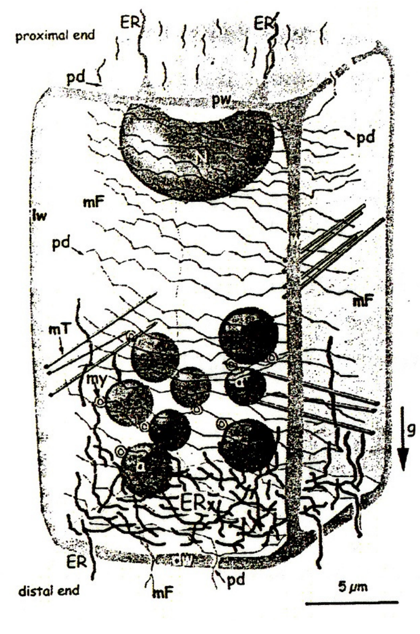


Figure 3.5. The figure illustrates some of the many constituents of a plant cell under centrifugation. N = nucleus, small dark particles = statoliths. Acceraltion direction indicated as is the linear dimension of cell.

*

A balance system can, as many other physiological systems, be considered as a stimulus - response system. A signal is sent into the system, where it works as a *stimulus* and brings about a *response* from the system.

In biology, stimulus-response relations are often studied while in physics and informatics one often speaks about *input-output* signal relations.

Experiments have been performed on earth to determine the necessary threshold value to get a balance reaction (or nemding, curvature) after a stimulus of plants. The best measurements indicate that at a stimulus of 1 g_n the necessary stimulation time is less than 15-30 seconds. *The balance system of plants is thus sensitive to stimulations shorter than 15-30 seconds*! Compared to our earlier calculations, the system works close to the threshold calculations we performed, based on the assumption that the threshold value was only determined by the thermal noise in the cell fluid.

It is, however, difficult to imagine experiments on earth that may help us in approaching a more precise determination of the biophysical threshold value. A possibility would be to repeat the experiment with a force weaker than 1 g_n , perhaps about 0,01 g_n. This would give another curve which could be used for the extrapolation. Since the force is weaker than 1 g_n, longer stimulation times must be used compared to the 1 g_n case. These longer time intervals would probably make it easier to identify a possible threshold value by the extrapolation procedure we have used.

Such experiments, with forces smaller than 1g, have in fact been performed in satellites in space. One have then used rotating centrifuges placed onboard Spacelab or ISS and one could apply accelerations less than 1 g_n, which is not possible in earthbound laboratories. One such experiment, GTHRES (why this acronym?) was an American-Norwegian experiment, in which threshold values for the balance system were studied.

A comparison of root growth under 1 g_n and in microgravity is given on the next page.
The figure demonstrates changes in the growth direction that occurs when plants are cultivated in microgravity. Normally the roots grow along the gravity vector (to the left of Fig. 3.6) – which defines the *set-point*. They loose this set-point and their orientation in microgravity (right of Fig. 3.6). Then the movements will be uncontrolled. The balance system will not function, as will also be the case in plant shoots and in animals in weightlessness. Picture is from a Norwegian Spacelab experiment denoted RANDOM.

It has been demonstrated that some plant parts are sensitive to acceleration forces as small as 0.001 g_n. But in order to produce a response of the plant the force must then be applied for a correspondingly long time! We conclude that it would not be a problem to cultivate plants when it comes to the balance system – if we try to do it on Mars with its gravity of about 40% of ours. (But there might of course be other obstacles!).

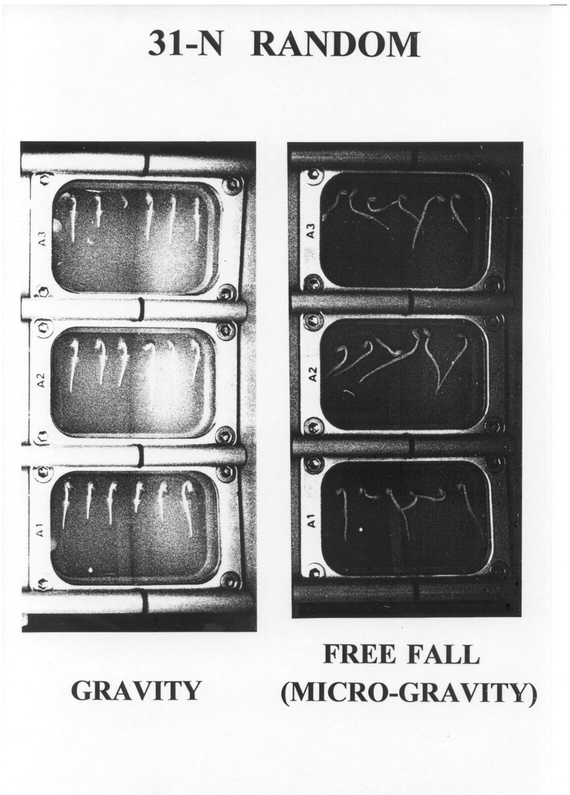


Figure 3.6. Root growth in 1 g_n and in free fall. Data from Spacelab experiment (plant on centrifuge to the left, in free fall to the right).

4. GRAVITY COMPENSATION IN EARTH EXPERIMENTS.

4.1. Introduction.

As we have seen, experiments in weightlessness are of importance in many different parts of natural sciences and technology. The costs of performing the experiments in Space is, however, quite high. Alternatives to Space facilities were outlined in Chapter 1: drop towers, parabolic flights etc.

But one has also to find suitable alternatives in Earth bound laboratories - alternatives that to some extent mimic the microgravity effects on organisms and systems and allow for other aspects of experiments. For instance, long-term experiments can not be simulated and replacements for a real long term Space experiment in weightlessness have not been found.

The use of substitutes for weightlessness can be quite important. The training of astronauts, for example, and their handling of tasks in space must be carried out on Earth and it would be dangerous not to train the astronauts to the highest performance possible before sending them into Space. We will mention some important test methods used before flight experiments in this chapter.

4.2. Use of buoyancy

As we have seen the buoyancy of water will partly compensate for the gravitational force, see Fig. 2.6. This everyday experience from swimming in water - especially of course, salt water with its higher density due to the salt concentration (of about 3,5%) - is used in the astronaut training.

Here not only the clothing can be tested but also the performance of tasks that should later be executed in the astronaut activities. Extravehicular Activities (EVA's) is the term used for astronaut activity outside the Space Shuttle or other Space vehicles. Several very important EVA's have been properly covered in the mass media. It is also to be observed that many complicated operations in space would not have been possible to achieve without proper astronaut work.

The Hubble observatory and telescope could be mentioned as an example of a very complicated, fully automatized undertaking that was launched successfully. After a certain time it was, however, necessary to carry out important repair work on the telescope since one mirror had to be adjusted. All the repair projects were successfully solved manually, after proper preparation on the Earth. Probably it would have been impossible to carry out the repair processes without human EVA's.

A picture showing the complicated testing of flight modules in a water basin is shown below. It demonstrates that much equipment is tested under water in the preparatory phases of a flight.

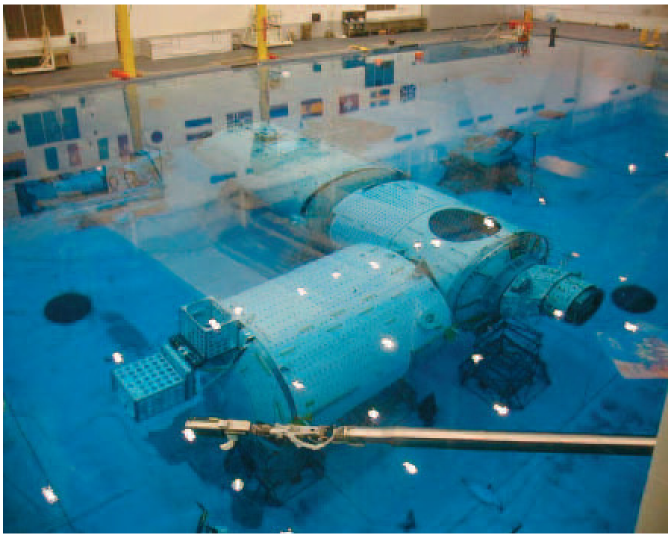


Figure 4.1. Columbus mock-up in the pool of a NASA Neutral Buoyancy Laboratory, where simulations of weightlessness have been performed for technical tests as well as for the training of astronauts (EVA operations - External Vehicular Activity). Photo: ESA

4.3. "Free fall" machine - "Jumping" machine.

An example of equipment that would be possible to use in some special cases can be outlined here. The parabolic flight was mentioned in Chapter 1, and it was found that the period of weightlessness was of the order of minutes in such experiments.

In some *physiological* experiments a so-called *free fall or jumping machine* can be said to be an alternative. Its principle is of general interest. If one drops an experimental container onto an elastic surface, it will jump up and regain a certain height above the surface, like, e.g., a tennis ball hitting the ground. Of course the container (or tennis ball) will continue to bump with continuously diminishing height until all energy is lost in friction. If, however, enough energy were used to give a kick to the container at each collision with the surface, it could be kept bumping up and down between its original height and the surface. The interesting feature with this system is that the container (or tennis ball) in fact would be under free fall under most of its trajectory. It simply behaves as a kind of parabolic flight machine.

The container falls under the action of gravity (free fall!) and during the collision, energy is transferred to the material structures of the container and the surfaces, both being compressed and in the next instant giving rise to the upward movement of the container into the air again. But as soon as the container has left the surface, only the gravity is acting again, i.e. the container is under free fall conditions. It will then go up to it highest point above the surface and then fall again onto the surface – it is a special case of a parabolic flight, see figure 1.7.

If the container now carries, let us say an insect, it would be possible to study the insect behaviour in free fall (allow a miniaturized CCD camera to be included in the container!). Our only concern is what could happen during the repeated collision processes? For a short time the container then changes its velocity from being directed downwards to being directed upwards, a force is of course acting on the container and the fly - and this seems certainly out of interest when studying microgravity effects! In some cases it might be useful all the same:

The critical thing here is the possible action on the system during the collision phase on the system. If the force experienced by the system (let us say a single cell) is "small" enough and the collision phase "short" enough then the product of the two will be "small". In the present context this means that the product - the *dose* – can be so small that the perception system of the cell can not perceive the collision accelerations.

Remembering that the dose can be defined out from

(*Acceleration* experienced) x (*stimulation period*) = *dose*

applied, we found earlier that the gravitropic system of plants had a threshold time for stimulation at one gn that was some seconds. The dose will therefore be about 5 g_n x s. Therefore, in this particular case a jumping machine must produce a dose that is less than this value in order to be useful.

4.4**. Random Positioning Machine, RPM.**

If a cell in a small multicellular organism is continuously moved around its x, y and z axis, its balance system will loose its reference direction. The organism may, for a short while, Δt_1, record the "down" direction in a certain direction (α_1). However, during next time interval, Δt_2, the same direction will be moved and point in another direction (α_2) etc.

The positioning of the organism during Δt_1 , Δt_2, etc will then give cause to stimulations in all angular directions as time goes by. If the positioning during the subsequent short time intervals, is controlled by a data machine in a random fashion, the organism will be without a fixed reference direction.

A machine providing such random positioning of the biological system is denoted a Random Positioning Machine, RPM. Any preferred "down" and "up" direction will be impossible to perceive by the organism. In a certain sense an RPM can, therefore, be used to simulate weightlessness.

A mass particle in a cell can, for example, be subject to forces in all directions, as sketched in the figure below (provided that the random position continues for a sufficiently long time). The integrated action of the movement might then be perceived by the balance system as an overall, averaged, stimulation leading to disorientation.

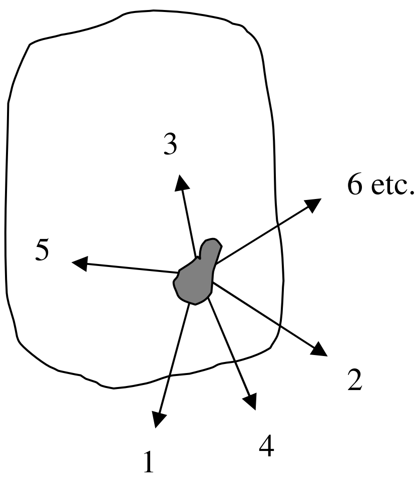


Figure 4.2. Basis for an RPM, Random Positioning Machine.
In the coordinate system of the cell, gravity will be directed in random directions as the machine is turning the cell in different directions. A sequence of gravity vectors can then be 1, 2, 3, 4, 5, 6 as indicated. The duration in the different position might also be randomly controlled.
Since the vectors are then random one assumes that the overall physiological action of the stimulations is nullified.

The length of the time intervals, Δt_i, must be chosen so that the net stimulation achieved over time will be nullified. This means in practice that a sensitive organ must be positioned with a sufficient speed so that any vectorial stimulation will be nullified within a reasonable experimental time. As a consequence, the RPM must change its random position fairly rapidly and *vibrations* etc. of the machine can result but must be avoided.

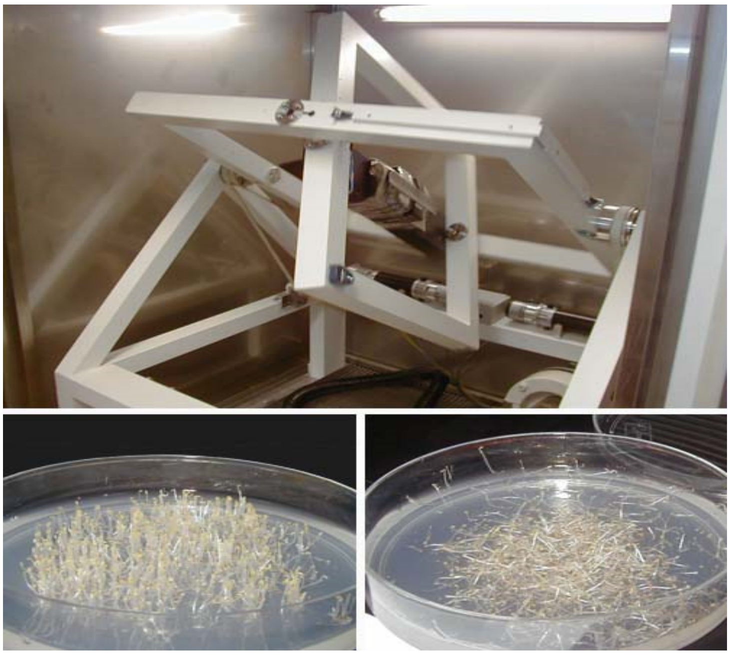


Figure 4.3. Random positioning machine, RPM. Plants grown on an RPM.
The machine allows the position of the experimental object to move around according to a program, that can create random directional position. Object in the centre of the machine.
Lower photos show plants (*Arabidopsis thaliana*) grown under 1 g, left, and on the RPM, right. The plants loose their directional growth on the machine when it is properly programmed.
Photo: Centro de Investigaciones Biológicas, Madrid

4.5. The clinostat.

The *clinostat* is a commonly used instrument to slowly turn cells, plants or plant organs around a (in most cases) horizontal axis. This does not eliminate gravity, but it may average out the vectorial stimulations given to the organ. However, it must be used with cautiousness and some considerations are pertinent.

Fig 4.4 shows a rotating cylinder (seen along the axis). It can symbolize an experimental cylinder in which we have (dense) cells or a cell itself in which we have dense particles. Some dense particles are drawn in black. The movement of the dense masses is dependent on several parameters, like the rotation rate of the cylinder, ω, the radius r, the fluid viscosity η etc.

If we release a dense mass in the axis position it will of course sediment to the cylinder bottom if ω is zero (cylinder stopped). If, however, the cylinder is slowly rotating the mass will follow a path in the liquid and might reach the cylinder wall or not, depending on the parameter choice. If suitably chosen the rotation can produce a situation in which the dense mass performs a closed circle path in the liquid. etc.

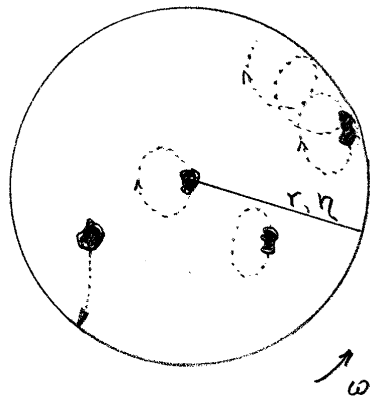


Figure 4.4. Basic principle of the so-called clinostat.

The cylindrical cell is mounted along a rotating horizontal axis (and is here seen from the axis direction). When the axis is rotating (angular velocityω) heavy particles will follow paths that are determined by the gravity, the relative density, the possible interference with the cell walls etc. Important parameters are, e.g. the radius r of the particles from the rotation axis and the viscosity η of the cell content.
In the rotating coordinate system of the cell, heavy particles can follow different trajectories as exemplified by broken lines. In some cases they will just stay in the cell liquid without touching the walls or, they will tumble along the cell walls. One assumes that this rotation causes uniform stimulation of the cell (if any), and that the directional action of gravity is then nullified.

If the particle was released at another point than at the origin, the path during rotation can be complicated. We can easily imagine that the situation can lead to a distributed contacts between the particles and the cylinder wall. This means that any vectorial stimulation will be nullified out over time. *This is the idea of the clinostat as a tool to imitate weightlessness: dense particles (like statoliths) will stimulate the cell in a non-directional way ("omnilaterally").*

One point of observation: if we have appreciable distances between the dense particles and the rotation axis the centrifugal accelerations must be taken into account. The rotation to keep the particles moving in the cell might, if ω is too high, cause a one sided acceleration of all dense particles in radial direction and a subsequent pressure on one of the cylinder sides. *Then we get a one-sided, non-compensated stimulation.*

We realize that a too high rotation rate will cause non-negligible centrifugal forces and, if we have a too big an object on the clinostat, that parts of it will be far off the rotation axis and will, therefore, experience a higher centrifugal force.

Usually one uses a rotation speed of about 1 – 2 rpm in physiologically used clinostats, the objects typically being less than a few centimetres.

4.6. Overview.

In this chapter we have tried to look at different methods to *simulate* free fall or weightlessness on the earth by

- buoyancy experiments,
- jumping machine experiments,
- random positioning machines,
- clinostats

In earlier chapters we discussed how rocket, air planes and satellites could be used to *generate* free fall conditions.

There are many tests that should be done on persons who would become astronauts, not only physical tests but also psychological and personality tests etc. We get a reminder of this when reading that the longest test with a crew of seven persons for a manned Mars-journey has now (summer 2015) started and should continue for one year. Test site is the volcano area Mauna Loa in Hawaii, at about 4000 m altitude (also with strong UV-radiation).

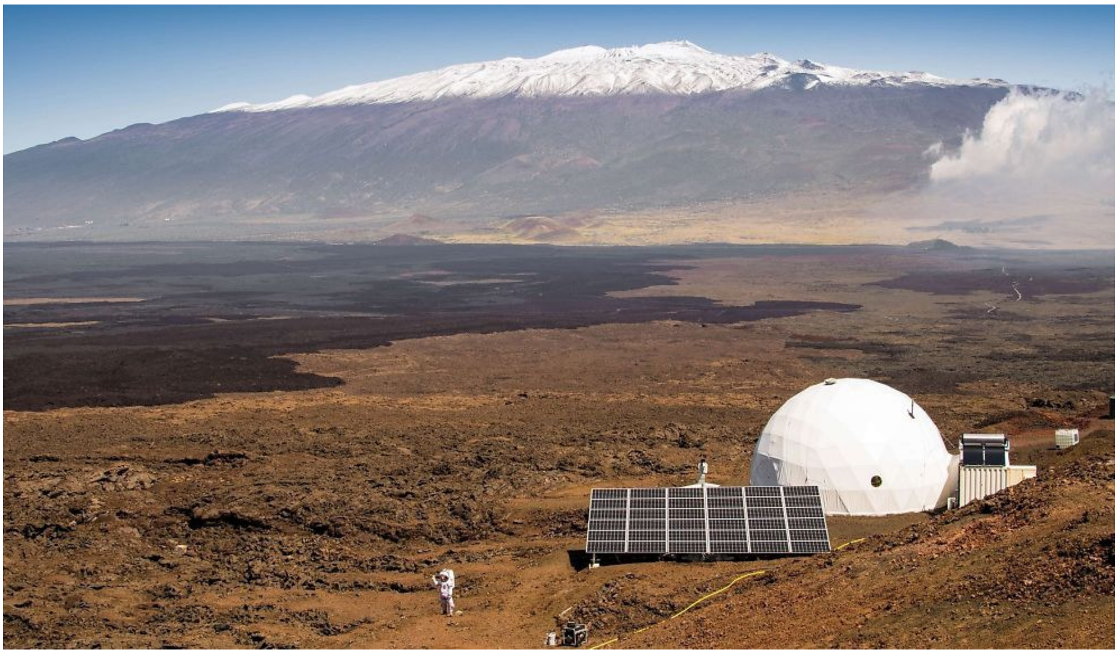


Figure 4.5 Test site, Mauna Loa, Hawaii. Foto: Neil Scheibelhut / University of Hawaii Afp

The team consists of one French astrobiologist, a German physicist and four Americans – a pilot, one architect, a journalist and an soil specialist. The previous long term experiments of this kind have been of 4 and 8 months duration respectively. The ‘dome’ has a diameter of 11 m and a height of 6 m.

Foto: Zak Wilson *Afp*

Figure 4.6. Inside view of experimental dome in Figure 4.5.