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# APPENDIX A1

# A PRIMER ON MECHANICS

> *When we were carrying on our wind-tunnel work we had no thought of ever trying to build a power aeroplane. We did that work just for the fun we got out of learning new truths.*
> Orville Wright, 1928 (in Kelly, 1996)

> *In the early twentieth century Albert Einstein revolutionised theoretical physics by overturning Newton's view of gravity. With it went Newton's view of the universe as permanent and unchanging. Although Einstein himself resisted it, the equations seemed to predict a dynamic universe.*
> Stephen Hawking, 1999

Mechanics is the science of forces acting on bodies at rest and on bodies in motion. The whole of mechanics is subdivided into statics, kinematics and dynamics.

- Statics deals with forces on bodies at rest and in general addresses the equilibrium of these forces by both external and internal reactions.
- Kinematics is the study of the relative motion of one or more connected or disconnected bodies or particles, without any reference to forces acting on them.
- Dynamics is the study of forces acting on bodies in motion.

## A1.1 STATICS

### A1.1.1 FORCES

As a helpful introduction to this aspect of mechanics we examine the types of forces and combinations of forces that can act on bodies or systems of bodies. We often talk about forces, but we equally often overlook the fact that a force is not an easily measured quantity. In fact in a most general way the concept (idea) of a force is based entirely on the "effect" it can create.

When we weigh ourselves on a simple bathroom scale, the effect created by our mass acted on by gravity is to displace a spring inside the scale. A pointer attached to the spring will then indicate the "force" of gravity acting on our body mass.

Figure A1. Schematic view of weightlifter action

Figure A2. Weightlifter in action

Similarly, when a weightlifter lifts a weight (refer to Figures A1 and A2), his muscles and bones react to the force of gravity acting on the mass of the weight being lifted. Isaac Newton recognised that two masses attract each other in proportion to their masses and inversely proportional to the square of the distance between their respective centres. The constant of proportionality in this relation is the "gravitational constant" G.

Acceleration due to gravity $g = (G \times M)/r2$, where

G = the gravitational constant = $6.673 \times 10\text{-}11$ m3 $kg^{-1}$ $s^{-2}$

M = mass of the earth = $5.974 \times 1024$ kg

R = the radius of the earth = 6,378,140 m at the equator.

The earth is a flattened sphere (referred to by geometers as a "prolate spheroid") and its radius at the poles is about 2100 m less than at the equator.

The current holder of the world super-heavy class (greater than 105 kg body weight) championship for "clean and jerk"[A1] is Hossein Reza Zadeh of Iran, who lifted 263.5 kg at the Athens Olympics in 2004. The clean and jerk lifting style is shown in the photo of Figure A2. It is instructive to calculate the relative effect on a record such as Reza Zadeh's if the weightlifting competition were held at Quito (capital city of Ecuador, through which the equator passes) and at Svalbard, on the Arctic island of Spitsbergen (at 78 degrees of latitude).

Forces can act as individuals or in pairs forming couples. A force is a vector quantity having magnitude, direction and sense and it is usually depicted as a directed arrow. They can act in a plane (called planar system of forces) and in three dimensions (called a "general system of forces").

A pure couple is a planar system of two equal and opposite forces separated by some distance. The effect of a couple is called a moment and the moment of a couple is measured by the product of the force and the distance between them. Moments are also vector quantities and may be represented by a directed arrow normal to the plane in which the couple acts.

Figure A3 shows a planar system of forces acting on a mathematically thin planar body called a "lamina". The forces are shown acting normal to the lamina at their

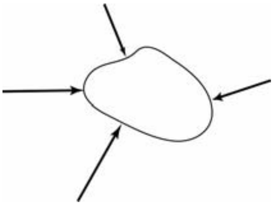

Figure A3 System of forces acting on a lamina

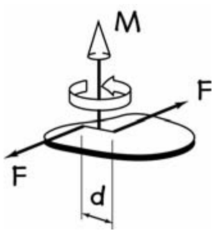

Figure A4 Moment of a couple M = d x F

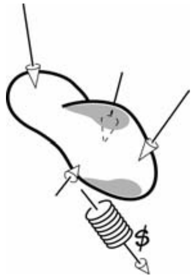

Figure A5 General system of forces acting on a body

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[A1] Clean and jerk is a two stage-lifting technique used in weightlifting, with each lifting stage raising the bar about half of the total lift.

point of application. This avoids the introduction of forces acting tangential to the lamina (friction forces, for example). Figure A4 shows a couple acting on a lamina. The moment of this couple is a vector M as shown. The sense of M is positive when pointing out of the lamina as shown. Figure A5 shows a general system of forces acting on a body. The combination of these forces results in a single general mechanics entity called a wrench, which is a combination of a general force and a moment acting on a single line called a screw. The instantaneous action of this wrench on the body is to twist it in a helicoidal field of motion about the screw. Although it is always useful to think of general systems of forces as wrenches, the treatment of screw geometry is beyond the scope of this simple primer.[A2] Moreover, for the purposes of simple structural and dynamic analysis, almost all of the systems of forces acting can be either represented by planar forces and moments, or resolved into such systems of forces and moments.

### A1.1.2 PLANAR PINNED STRUCTURES

For systems of planar forces a basic rule of Newtonian mechanics is that for these forces to be in equilibrium (*i.e.*, the lamina should not move under the action of these forces) is that:

(a) Either the lines of actions of all the forces should intersect at one point (*i.e.*, they should be concurrent), or

(b) Their lines of action should be parallel (i.e. their point of concurrency is at infinity according to Euclidian geometry), and

(c) To every action (applied force or moment of forces) there is an equal and opposite reaction (equilibrating force or moment of forces).

When we build simple structures the most important consideration is that the structure should support the loads (forces and moments) imposed on it. These forces and moments will generate internal forces and moments in the material of the structure and eventually these internal forces and moments will cause the material of the structure to break or deflect too much.

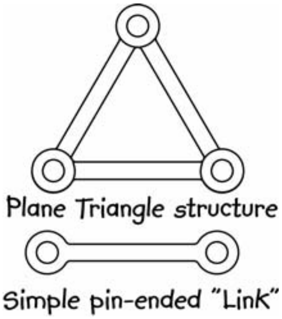

Figure A6 Simple structural elements

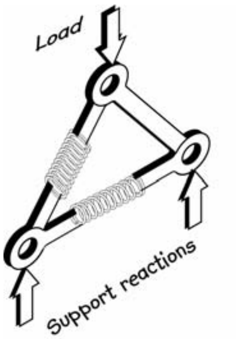

Figure A7 Pinned planar structure under load

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[A2] See Papastravidis (2002) Davidson and K. H. Hunt (2004)

Simple load bearing structures are often constructed from several simple parts connected together. The simplest part of a structure is sometimes referred to as a link, signifying the linking together of several parts of the structure. When such simple structures are subjected to external loads, the loads are distributed into the several links making up the structure. We make various simplifications about the nature and behaviour of such links in structures. These simplifications permit easy evaluation of the forces generated in the links.

Figure A6 shows a simple pin-ended link and the simplest type of plane structure we can construct using only the links and pins inserted at the joints between each pair of links. The following are the simplifications usually applied to allow simple analysis for internal link forces:

- Although the real structure must have some thickness (in the direction perpendicular to the paper on which it is sketched), the applied loads and internal link forces generated will all act in the same plane;
- The pins at the joints and the faces of the links are all "frictionless".

A useful way to think about the forces in the links of such a structure is to imagine the links replaced by springs and also imagine how these springs will deflect under some externally applied load. Figure A7 shows two links replaced by springs and clearly the horizontal link spring will be expanding and the two angled links will be contracting under the applied external loads. These deformations then give us clues about the nature of the internal loads generated in the links by the externally applied loads. In more complicated structures this simple approach will not be easy to apply, but with experience even some complicated three-dimensional structures will yield to this imaginary evaluation. Many commonly used planar structures are built up from such triangles and the resulting trusses are referred to as triangulated trusses. Figure A8 shows some simple triangulated trusses used in bridges and roof construction. The types of forces generated in planar frictionless pin-jointed structures may be classified as follows:

(a) Tensile forces - The structural element that carries only this type of load is called a "tie";

(b) Compressive forces - The structural element that carries only this type of load is called a "strut".

The load-bearing capacity of any member of a structure depends on a combined relationship among applied load, cross-sectional area of the structural element

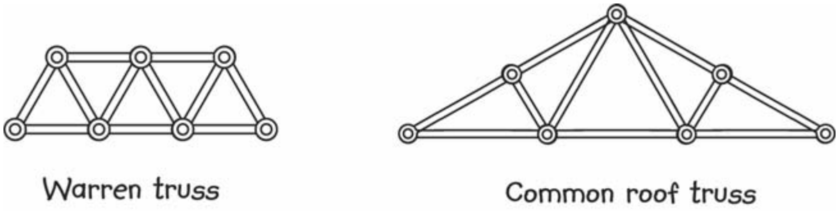

Figure A8 Simple triangulated planar trusses exposed to the load and the mechanical properties of the material from which the component is made. For a useful and instructive introduction to mechanical properties of materials interested and enthusiastic readers are referred to J.E. Gordon's *Structures or Why Things Don't Fall Through the Floor.*

The material's properties are usually established by standardised tests involving standard test specimens made from the material of interest. These test specimens have a well-defined area of cross section over which the load is presumed to be acting uniformly. The tests are performed both in tension and compression and, in general for metals, the values obtained for mechanical properties are similar in both types of loading. However, the ultimate failure of a test specimen (or indeed a structural component) in tension is associated with the specimen (or component) physically breaking apart. For the sake of simplicity only the tensile properties are described here.

All elastic materials have the property of elasticity, or the capability of regaining their unloaded shape once the load is removed. The limit of elasticity is the condition when the load applied is so great that the material can no longer resume its former shape once the load is removed. In metals this limiting condition results in some permanent deformation of the material and the material is said to have sustained permanent set or to have sustained plastic deformation. The reference to plastic signifies the distinctive difference between elastic materials and plastic materials, the latter being unable to regain shape after a load is removed. Figure A9 is a graphic representation of the load deformation behaviour for a ductile metal.

The load and deformation are made universally applicable for the specific material by expressing them respectively as stress (load/unit area) and strain (deformation/unit length). The symbols commonly adopted for these measures are as shown, $\sigma$ for stress and $\varepsilon$ for strain. The ratio of stress/strain in the elastic region of the material, denoted E, is called the "modulus of elasticity", or "Young's modulus", after Thomas Young (1773-1829), the English physicist who first formalised the measurement of this property.

The specific mechanical properties of materials of interest to us are:

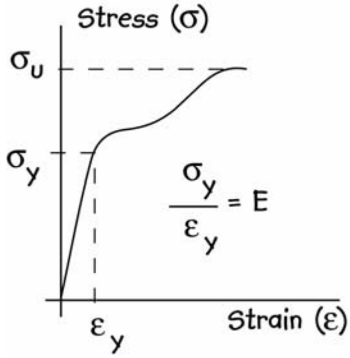

Figure A9 Load-deflection behaviour of a ductile metal (steel, for example)

- Ultimate tensile strength, defined as the load per unit area of the test specimen (or stress-with the units of pressure) when the specimen breaks. The symbol used for this property is $\sigma_U$;
- Elastic tensile strength or more commonly "yield strength" is the load per unit area of the test specimen when the material reaches its elastic limit and begins to deform plastically. The symbol used for this property is $\sigma_y$;
- Modulus of elasticity E.

The relationship among these properties in the elastic region of the material follows the well-known form for elastic materials originally expressed by Robert Hooke(1635-1703), now known as Hooke's Law,

$$\sigma = E \times \varepsilon.$$

The task of the designer is to ensure that the loads carried by members in structures do not exceed their elastic limits. In this way we can guarantee that the structure will suffer no plastic deformation. Once the loads acting on the ties and struts in a plane frame are found, the size of the component will be determined by its material properties. When we design for strength (stress-limited design), the area of the strut or tie is found from the ratio of internal load and allowable material stress. For example, a tie constructed from 1.86 mm dry spaghetti will carry a load of approximately 54 N or 5.5 Kg mass[A3].

Occasionally we are required to design a structure for minimum deflection (deflection limited design). In that case the elastic properties of the material will govern the size of the tie or strut. In this case we make use of the stress/strain relationship of the material and its elastic modulus as expressed by Hooke's Law for the material.

A further complication is encountered with struts that are slender. A formal definition of the slenderness of struts is derived from elastic theory due to the eighteenth century Swiss mathematician, Leonhardt Euler. Without proof it is stated that a pin-ended strut is regarded as "slender" when

$$L > \sqrt{\frac{2\pi^2 E}{\sigma_y}},$$

where L is the length of the strut, A is its section area, I is called the "second moment of area" of the section and is a measure of the capacity of the section to offer resistance to bending, E is the elastic (Young's) modulus and $\sigma_y$ is the yielding tensile strength of the material of the tie. Yielding is a form of material failure corresponding to the stress level where the material begins to deform plastically (can no longer recover its original shape when the load is removed).

Slender struts can suffer a form of elastic failure called "buckling". This is a failure form that occurs at much lower loads than the compressive failure load of the material and it is elastic because once the load is removed the strut can recovers its unloaded shape. Unfortunately the effect of a buckled strut is that once it has buckled, it can no longer support any loads and the compressive load originally carried by this strut will be redistributed to other members in the structure. Again without proof, the buckling load in a pin-ended slender strut was derived by Euler as

$$P_{buckling} = \pi^2 EI/L^2,$$

where the symbols have the same meaning as before.

### A1.1.3 BENDING

When a load is applied transversely to a single structural element, the resulting deformation is referred to as bending. The structural element carrying a bending load only is referred to as a "beam". The distinctive character of beams and their load-

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[A3] Refer to Table 4.6 for data on the strength of dry spaghetti.

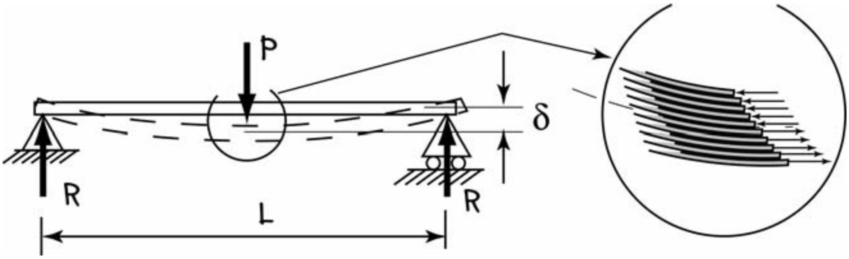


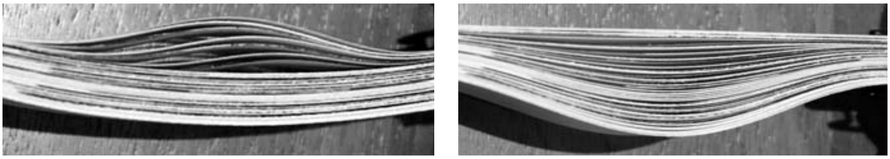
Figure A10 Beam in bending and a grossly exaggerated midsection of the bent beam

carrying behaviour is often described by the type of supports used for reacting against the applied load.

Beam theory applies to small ($\delta$ much less than L) deflections only. Under these conditions the curvature of the deflected beam is also small. Another approximation invented to permit evaluation of the internal stresses due to bending is indicated in the exaggerated midsection of the deflected beam in Figure A10. The beam is considered as several thin laminations of material deforming as indicated. The approximation implies that the laminations of the beam behave as do (say) a deck of cards or a stack of thin cardboard when bent.

If we perform an experiment holding a stack of thin cardboard between thumb and forefinger and bending the stack, we find that we need to apply some inward push on the top of the stack and some outward pull on the bottom of the stack. This effect indicates that to permit bending such a stack the upper regions of the cardboard laminations need to experience some compression and the bottom regions must experience some stretching. Somewhere at the centre of the stack there will be no deformation. This central undeformed mathematically thin lamination of a beam is called the neutral surface of the beam. During this bending process the deformed cardboard laminations slide over one another to allow the stretching and compressing to occur.

Figure A11 shows a simple experiment performed to illustrate the model behaviour of laminations in a material when experiencing a small bending load. In Figure A11 (a) the top layers of the cardboard stack are buckled by the compression loads experienced there under bending. Because the thin cardboard laminations are much stronger in tension than in compression, the bottom laminations have slid through the



(a) (b)

Figure A11 A stack of cardboard held firmly together by spring clips is bent and then straightened

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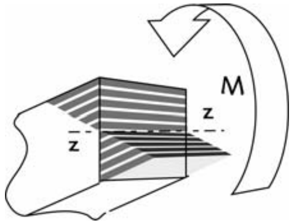
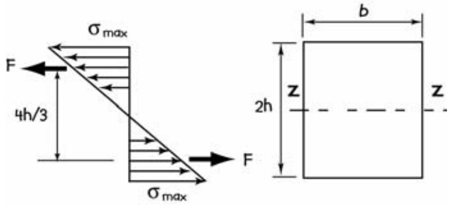
|  |  |
| Figure A12 Beam cross section and moment due to bending generating tensile and compressive loads in the beam material | Figure A13 Beam cross section and forces acting due to bending load represented schematically |

spring clips holding the stack together. In the solid material beam these laminations will actually experience stretching. This is illustrated in Figure A11 (*b*) by the extra length gained by the bottom laminations once the cardboard stack is straightened out. With these approximations we can evaluate the maximum stress in the beam material, generated by the bending load applied.

Figure A12 shows schematically the tensile and compressive loads generated in the beam material by the moment M applied to the beam. Figure A13 shows these tensile and compressive loads expressed as stresses acting on the beam material.

$$F = b \times h \times (\sigma_{max}/2),$$

$$M = 2bh^2(\sigma_{max})/3, \text{ and hence}$$

$$\sigma_{max} = 3M/(2bh^2).$$

For the section shown in Figure A12, the expression $2bh^2/3$, often denoted "Z" in beam theory literature, is called the "modulus of the section". Another important expression (h x Z or $2bh^3/3$ for the section shown in Figure A13) denoted $I_{zz}$, is called the "second moment of area" about the axis zz and it is a geometric measure of the section's capacity to resist moments applied to the section about the axis zz.

As noted earlier, beams or structural members subject to transverse loads are often described by the nature of their supports as well as the applied loads. This description helps us to visualise the character of the stresses generated in the beam by the applied loads. The example of Figure A10 above shows a simply supported beam under the action of a single concentrated load. The terminology "simply supported" means that there are no forces or moments imposed on the beam by the supports themselves. The maximum moment in the beam and the associated maximum material stress may be calculated from the equilibrium conditions of the beam and applied load. In the example of Figure A10 the maximum moment $M_{max}$ for a centrally loaded beam is PL/4, and then the resulting maximum tensile or compressive stress in the beam will be at its top and bottom surfaces as indicated in Figure A13.

$$\sigma_{max} = \pm 3\,PL/(8bh^2),$$

and, by convention, we associate the negative sign with compressive stresses.

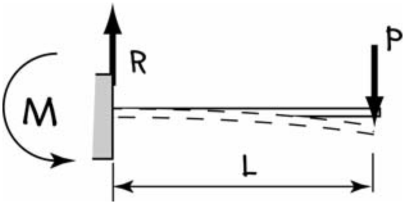


Figure A14 Cantilever beam

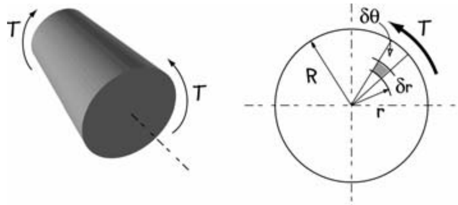


Figure A15 Cylindrical rod in torsion

Figure A14 shows a cantilever beam also under the action of a single point load. With this type of beam the one support is built in and provides the reaction load as well as the equilibrating moment necessary to maintain the whole system in equilibrium. Loads on beams may be distributed over the whole beam and in many practical cases of beams both ends may be built into their supports.

The deflection of beams is derived from the differential equation for the shallow curvature of the beam for small deflections. Although deflection theory is outside the scope of this brief introduction, it is worth noting that for the beam examples in Figures A10 and A14 the maximum deflections are $PL^3/48(EI_{zz})$ and $PL^3/3(EI_{zz})$, respectively.[A4]

## A1.1.4 TORSION

Bending of a beam resulted in some internal stresses generated in the beam material. We have evaluated these direct stresses in the previous section. However, as the idealised thin laminations of the beam material are stretched and compressed during bending of the beam another stress is also in action. Perhaps we could think of these other types of stresses, called shear stresses, as resulting from the frictional effects of the thin laminations stretching and compressing relative to each other during bending. Most commonly, shear stresses result from a twisting or torsional load applied to a component in a structure.

Figure A15 shows a cylindrical rod under the action of an applied twisting load called Torque T. This torque generates shearing stress in the rod material and Figure A15 is an idealised schematic of how the torque is related to the shear stress in the rod. We can think of the shear stress, usually denoted as "$\tau$", varying from zero at the centre of the rod to $\tau_{max}$, a maximum at the outer surface.

The small component of torque $\delta T$ acting on an elemental area (shown shaded in Figure A15) is given by

$$\delta T = r \times \tau_r \times \delta r \times r\delta\theta \, .$$

Because the shear stress varies linearly, from zero in the centre to $\tau_{max}$ at the outer surface, we can write the value of the local shear stress at the elemental shaded area as

$$\tau_r = \tau_{max} \, r/R,$$

and the total torque as

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[A4] The interested and enthusiastic reader will find an excellent account of the development of these and other beam equations in Timoshenko (1953).

$$T = \frac{\tau_{max}}{R}\int_0^R \int_0^{2\pi} r^3 d\theta .dr$$

Integrating and transposing results in

$$\tau_{max} = 2T/\pi R^3.$$

The term $\pi R^4/2$ is a very important geometric property of the section of the cylindrical rod carrying the torque loading, known as the polar moment of area, usually denoted "J" or sometimes "Ip". This property is a direct measure of the capacity of the section to carry the torque load. The term J/R is the polar modulus of section analogous to the modulus $Z = I_{zz}/h$ for the beam in bending.

## A1.2 DYNAMICS

### A1.2.1 FORCE AND ACCELERATION

When a body, capable of motion, is acted on by a force, in general it will experience acceleration proportional to the force acting on it. If the force and the direction of motion are aligned then by the rule of motion due to Newton

$$F = m\,a,$$

where F is the force acting, m is the mass of the body and a the resulting acceleration of the body. In dealing with problems of motion and acceleration we often make simplifications about level and smooth (frictionless) surfaces, on which our accelerating body moves. Figures A16 and A17 show, respectively, examples of a body accelerating under the action of a force (linear acceleration) and a rotating body under the action of a torque (angular acceleration).

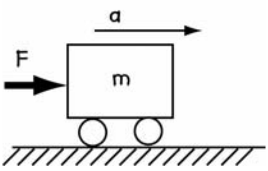

Figure A16 A body accelerating under the action of a force F

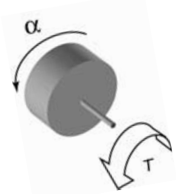

Figure A17 A rotating body accelerating under the action of a torque T

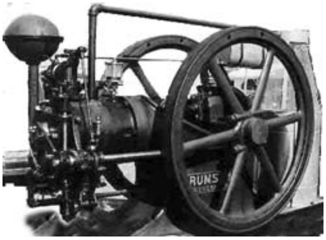

Figure A18 A Rumsey engine. Note the concentration of mass at the outer periphery of the flywheel

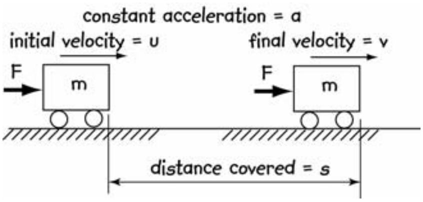

Figure A19 A constant force acting on a body experiencing constant acceleration

For the angular acceleration case, shown in Figure A17, we can apply the rule for rotating bodies (also due to Newton), analogously to linear acceleration

$$T = J\,\alpha\,,$$

where $T$ is the applied torque, $\alpha$ is the angular acceleration and J is a property of the rotating body called the moment of inertia, though sometimes mass moment of inertia to distinguish it from the geometric property we have identified here as the second moment of area, which is occasionally still referred to (quite inappropriately) as the moment of inertia for the section.

The value of this property J depends on the way in which the mass is distributed in the rotating body. Masses farther away from the axis of rotation contribute more to the value of J than those nearer the axis of rotation. This is the reason why flywheels, devices that are used to smooth out the speed variations in intermittently energised devices (such as internal combustion engines) often have their masses concentrated near the outer periphery of the wheel (see Figure A18, a type of engine manufactured by the L.M. Rumsey Manufacturing Co. in St. Louis, Missouri between 1881 and 1917).

There are several useful relationships between time (t), acceleration (a), distance covered (s) and velocity (v) that can be derived using Newton's rules of motion. We only derive these relationships for constant acceleration (or constant force) acting on bodies moving on smooth surfaces without loss. Refer to Figure A19.

For the example shown in Figure A19 we can write that

$$s = \int_0^t v\,dt = \left[\int_0^t a \bullet dt = u + at\right] dt = ut + {at^2}/{2}\ .$$

This equation relating distance covered to elapsed time and acceleration invokes the facts that the body has some initial velocity u and that acceleration is constant in time.

From the work done by the force F we find that the energy change incurred by our moving mass is $M\,(v^2 - u^2)/2 = F.s = M.a.s$. Cancelling the mass and rearranging we get

$$v^2 = u^2 + 2.a.s\ .$$

Similar expressions may be written for constant torque $T$, acting on a rotating body experiencing constant angular acceleration $\alpha$ . The displacement for rotary motion is expressed as the angle $\theta$ rotated. Using arguments similar to those for linear motion above, and using $\omega_1$ as the initial angular velocity and $\omega_2$ as the final angular velocity we get

$$\omega_2 = \omega_1 + \alpha t,$$

$$\theta = \omega_1\,t + \omega_2 t^2/2,$$

$$\omega_2^2 = \omega_1^2 + 2.\alpha.\theta.$$

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A5 An instructive and easy read on this topic is Peter Atkins' book *Galileo's Finger* (2003). This book, among other interesting material, offers a fine introduction to physical science and the mechanics of work and energy.

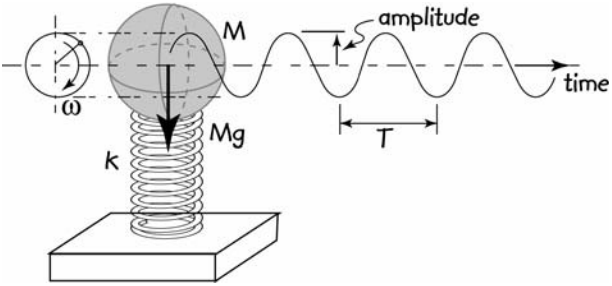

Figure A20 Simple harmonic oscillations of a spring-mass system

### A1.2.2 WORK AND ENERGY[A5]

When a force moves a body it is said to do work. Energy of a system (same units as work) is its capacity to perform work. Various forms of energy are interchangeable. For example, thermal energy may be used to do mechanical work (say) on a spring and thereby store potential energy in the spring. Alternatively a falling mass may exchange its potential energy for kinetic energy of motion. Invariably energy is used to perform some form of work and in so doing, as in the exchange of energy from one form to another, we incur some losses. These ideas are formalised in the various rules associated with thermodynamics (the study of heat work and energy exchange). In this brief primer only some simple examples of energy and work are noted, because the study of thermodynamic principles is outside the scope and intention of this appendix.

Probably the simplest form of energy exchange takes place in an oscillating spring, as indicated in Figure A20. The ball of mass M is given a small downward displacement "y" say and then released. The restoring force of the spring will be k.y (Hooke's Law again), where k is the spring stiffness, measured as a force required for unit displacement of the spring. In a sense k is the elastic modulus (see the stress/strain relationship in Figure A8) of the spring. The resulting motion is an oscillation of the spring mass combination about the resting position of the mass (*i.e.*, the mass is displaced Mg/k downward from its position when placed on the uncompressed spring), and this is the position about which the oscillations will occur. The form of the motion is described as simple harmonic motion and corresponds to the projected motion of a point mass executing steady rotation about the rest position of the centre of the mass M. The motion is called harmonic because displacement is a sinusoidal function of time and is related to the way musical instruments vibrate to produce sound. The sound produced by musical instruments is a complex combination of many harmonics.

The differential equation of the motion is written (from Newton's rule F = Ma) as

$$Mg - ky = M\, d^2y/dt^2.$$

The solution to this equation is

$$y = A\, \mathrm{Sin}(\omega t - \phi) + B.$$

Differentiating this solution twice and substituting into the original equation yields

$$\omega = \sqrt{\frac{k}{M}},$$

and B = k/Mg = the original displacement of the spring by M when at rest.

The frequency of oscillation

$$f = \omega/2\pi$$

and the period

$$T = 1/f.$$

The amplitude of the oscillation is found by substituting into these equations the initial conditions.

Clearly, when the mass M is at either extreme of its motion, the spring will have potential energy stored in it. This potential energy is then exchanged with the mass to accelerate it towards the centre of motion where the mass will have maximum kinetic energy. In this simple example we have neglected the mass of the spring. It is an instructive exercise (left for the enthusiastic reader) to consider the influence of the spring mass on the resulting motion.

The value f is a property referred to as the natural frequency or fundamental frequency of spring-mass systems. The form of the relationship

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{M}}$$

may be applied in a wide variety of mechanical systems where we can identify the stiffness k and the vibrating mass M. As a simple example we can apply this fundamental concept to the vibration of the beam of Figure A10. From the deflection formula given $\delta = PL^3/(48EIzz)$ we find that

$$k = P/\delta = 48\ EIzz/L^3.$$

Consequently for that beam carrying a load of P and having a self mass M we can write for the natural frequency of lateral vibration

As an instructive exercise (left for the enthusiastic readers) show that the natural

$$f \bullet = \frac{1}{2\pi}\sqrt{\frac{48EI_{zz}}{(M + P/g)L^3}} \bullet.$$

frequency of lateral vibration is approximately 61 Hz for a simply supported steel beam with the following properties: L = 1 m, 0.05 m x 0.05 m cross section, carrying a load of 100 N (Steel has a density of 7840 kg/m3).

Another type of system that exhibits harmonic oscillations is a simple pendulum. When the mass of the pendulum is released from some height, its potential energy is converted to kinetic energy of motion and in turn this is reconverted into potential energy as the pendulum swings back to its starting point.

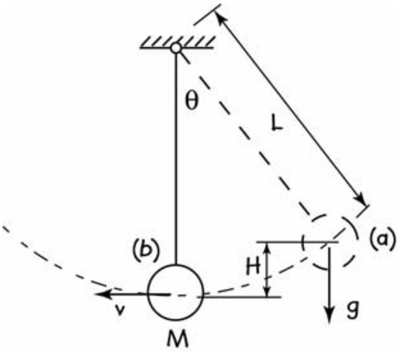

Figure A21 Simple pendulum

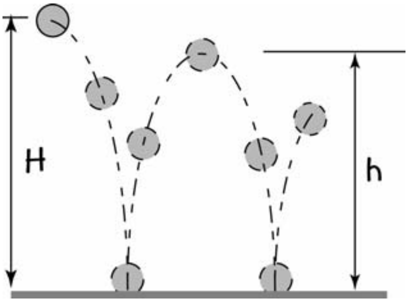

Figure A22 Bouncing ball

Figure A 21 shows a simple pendulum executing small angle oscillations where $\theta$ is of the order of 5°. The need for this simplification will become clear when we carry out the simplified analysis of motion for this pendulum.

At location (a) the pendulum mass has potential energy of MgH. At location (b) the mass has lost its potential energy, but gained kinetic energy of $Mv^2/2$.

If the pendulum suffers no losses, then we can equate the two energies and find that

$$gH = v^2/2 \text{ (the mass terms cancelling).}$$

This energy exchange continues indefinitely if the pendulum experiences no losses. The differential equation for this case is found by applying Newton's rule for circular motion, Torque $T = J\, d^2\theta/dt^2$, where J in the case of the simple pendulum shown in Figure A21 is $ML^2$, because the mass M is assumed concentrated at its centre.

Torque $T = L.\ M.g.\ \sin\ \theta = M.\ L^2.\ d^2\theta/dt^2$, and simplifying this we get

$$g/L\ \theta - d^2\theta/dt^2 = 0,$$

where we have substituted $\theta$ for Sin $\theta$ when $\theta$ is sufficiently small (as indicated earlier).

This differential equation is of the same form as that found for the spring-mass system above and the pendulum will perform simple harmonic oscillations for small values of $\theta$. The period of oscillation is T and depends only on the length L.

$$T = 2\pi\sqrt{L/g}$$

This is why the simple pendulum is such a fine timekeeper. Considerable effort was devoted by early clockmakers to maintaining L constant, independent of weather conditions.[A6] As a result a commonly used metal for pendulum arms in clocks is invar (short for invariant), a nickel–iron alloy that has been named for its tolerance to modest temperature changes.

Figure A22 shows schematically the behaviour of a bouncing ball dropped onto a hard surface with some initial horizontal velocity. The soft rubber ball, as it falls towards the hard surface, will exchange some of its potential energy for kinetic ener-

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[A6] See, for example, Sobel (1995), the story of James Harrison, the inventor of the marine chronometer.

gy and at impact into yet another form of energy, stored elastic energy. The whole process will reverse itself with some loss in both elastic recovery and in air resistance. The loss in elastic recovery is measured by the "coefficient of restitution" (rebound height/drop height) a property of the elastic material. For the case example shown in Figure A22 the coefficient of restitution is h/H. There are some materials with coefficients of restitution close to unity and the ball in those cases will return to almost the original height from where it was released.

Some typical coefficients of restitution are:

- Basketball = 0.66,
- Baseball = 0.54,
- Golf ball = 0.75.

Some simple expressions for energy are:

- The potential energy of a mass M at height H = M x g x H, where g is the acceleration due to gravity;
- Kinetic energy of a mass m moving with velocity v = m x $v^2/2$;
- Kinetic energy of a flywheel rotating at angular velocity $\omega$ with mass moment of inertia J is $J\omega^2/2$;
- Potential energy of a spring of stiffness K Newton/meter compressed (or deflected) by L meters = K x $L^2/2$;
- Thermal energy change in a mass M of liquid when this mass experiences a temperature change of $\Delta T$ = M x s x $\Delta T$, where s is called the specific heat and is a property of the liquid.

Energy available from burning fuel materials is based on the energy content of the specific fuel and the rate of burning. For example, paraffin (the basic fuel content of candle wax) has 42 kJ/gm of specific fuel energy. As an instructive exercise we could estimate the power (rate of working or rate of dissipating energy) available from a candle. The exercise requires that we burn a candle and time the rate of loss of candle material over some period of time.

## A1.3 VERY ELEMENTARY GAS DYNAMICS[A7]

Inasmuch as a compressed gas may be used as a primary energy source in MaT project construction, we need to define and explore some basic ideas about compressed gas behaviour.

Almost all the basic behaviour of gases was developed by scientists in the eighteenth and nieteenth centuries, when performing experiments that involved heating and pressurizing gases. The *Encyclopedia Britannica* notes:

> Among the most obvious properties of a dilute gas, other than its low density compared with liquids and solids, are the great elasticity or compressibility

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[A7] There are many useful references that help to introduce this topic more deeply than is possible in this brief exposition. See, for example, Zucker and Biblarz (2002); Hodge and Taylor (1999); Reiner-Decher (1994); Jones and Dugan (1996); Mayhew and Hollingsworth (1996); Moran and Shapiro (2000).

and its large volume expansion on heating. These properties are nearly the same for all gases and ... can be described quite accurately by the following universal equation of state:

$$pv = RT\ .$$

This expression of behaviour $pv = RT$ is known as the "ideal gas law". Although most gases behave very closely according to this law, there are some small variations from it at low temperatures. In this expression $p$ = pressure, $v$ = "molar volume", $T$ is the "absolute temperature" and $R$ is the universal gas constant.

In order to continue this discussion we need to define some of these basic ideas. The general view of gas behaviour is based on the idea that the molecules of gas in a given contained volume of gas are all moving and colliding and bumping into the walls of the container. Figure A23 is a schematic picture of a gas contained in a rectangular vessel.

The idea of very low temperatures has fascinated physics researchers since it was realised that all matter behaves strangely when temperatures are cooled to near absolute zero. The adopted value for zero Centigrade on the absolute temperature scale is 273.15 K (for Kelvin, a temperature scale named after Lord Kelvin of Largs, also known as William Thompson; 1824–1907, Scottish engineer and physicist), corre-

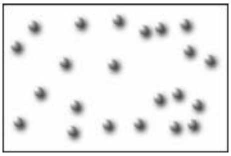

Figure A23 Schematic picture of a gas. The molecules of the gas move about in their container. For "perfect gases" the motion becomes more rapid as temperature increases and all motion will cease and the "perfect gas" gas will take up zero volume at the "absolute zero" of the temperature scale

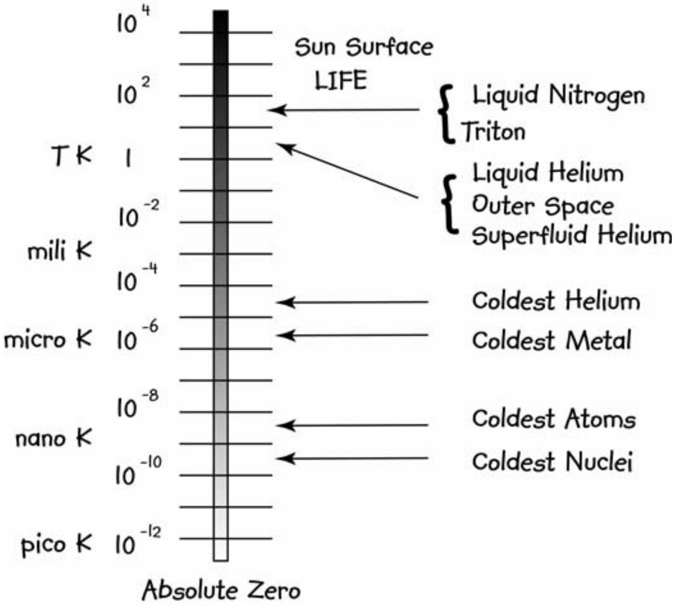

Figure A24 The Kelvin absolute temperature scale (shown logarithmically). Triton is the largest satellite of Neptune and mainly consists of nitrogen ice sponding to the temperature at which solid, liquid and vapour phases of water are in equilibrium with each other. This "triple point" of water occurs at 0°C or 32°F and 273.15 K (absolute) to make the "ideal gas law" the simple form it is. Although absolute zero (-273.15°C)cannot be reached, temperatures near this value have been attained in laboratory experiments. The scale of temperatures shown in Figure A24 is due to Professor Michael Lea, The Low Temperature Physics Group, University of London.

Molar volume is the volume of "one gram molecule" of a gas, where the gram–molecule measure is the molecular number of the gas in grams. For air, a mixture of oxygen and nitrogen, the average mole is 29 gm and even though it is a mix of two gases, the behaviour of the mixture closely follows the ideal gas law above.

The ideal gas law is a combination of three earlier laws. The first one is Boyle's law, named after the Anglo-Irish scientist Robert Boyle (1627–1691), who in 1662 discovered that, at constant temperature, the volume of a gas is inversely proportional to its pressure. The second law is due to Jaques-Alexandre-Cesar Charles (1746–1823), a French physicist, who discovered that, at constant pressure, a given quantity of gas has a volume directly proportional to its absolute temperature. The third law is that due to Amadeo Avogadro (1776–1856), an Italian physicist, who showed that, at a given temperature and pressure, equal volumes of gases contain the same number of molecules. This number (approximately) $6 \times 10^{23}$ is called Avogadro's number. For example, the molecular weight of oxygen is 32, and hence 32 gm of oxygen at 0°C (273 K) and atmospheric pressure (usually referred to as "standard temperature and pressure" or STP) contains $6 \times 10^{23}$ molecules. R is the universal gas constant and has the value 8.3143 J/mole °K.

Now applying the ideal gas law, we can confirm that one gram molecule of oxygen has a "molar volume" of 22.4 litres. Similarly, one mole of air has a mass of 29 gm and has a volume of 22.4 litres. Two other definitions relate to the heat energy needed to raise the temperature of a gas. There are two "specific heats" defined and they are denoted $C_p$ and $C_v$.

> $C_p$, as the subscript implies is the heat energy required to raise the temperature of a mass of gas by one degree Centigrade (or Kelvin), while the gas is maintained at constant pressure.
>
> $C_v$ is the specific heat defined for the gas at constant volume. These two constants for any gas are related by the universal gas constant as $R = (C_p - C_v)$.

We can now examine the behaviour of compressed air as an energy source. A useful form of compressed air energy source is offered by a plastic 1 litre beverage bottle. With a suitably modified bottle top, the air in the bottle may be pressurised to about two atmospheres, with either a bicycle pump or a small portable electric pump. If now we have a means of releasing the compressed air to do mechanical work, the estimate of available energy is approximated by assuming that the compressed air is exhausted to atmospheric pressure. In that case the work done on the environment by the compressed air is the same as the work done by the environment in compressing the air. Figure A25 is a plot of pressure against volume for a gas. The work done in compressing the air is the area under the graph or

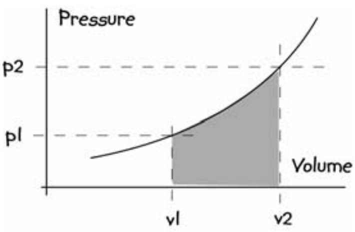

Figure A25 Pressure volume curve for air when being compressed from one atmosphere to two atmospheres

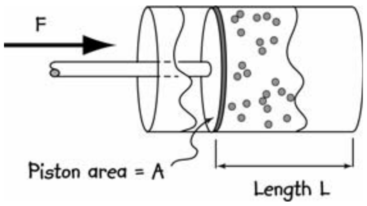

Figure A26 Gas "spring" behaviour

$$w = \int_{p1}^{p2} p\,dv\ .$$

The shaded area under the curve is the work done by the environment on the gas as it is being compressed. We assume the ideal condition that all this work can be recovered as the gas is permitted to expand freely. If the expansion takes place rapidly, as would be the case when the gas is unconstrained, then the expansion (compression) curve is said to be "adiabatic" and the index of expansion (compression) is $\gamma = C_p/C_v$. For air the value of $\gamma$ is approximately 1.3 and the relationship between pressure and volume is $pv^{\gamma}$ = constant.

For the case of 1 litre air compressed to (say) two atmospheres and then permitted to expand into atmospheric air, the values of volume and pressure are:

$p_1$ = 206,000Pa; $p_2$ = 103,000;

$v_1 = 10^{-3}m^3$; $v_2 = (p_1 v_1^{\gamma} / p_2)^{-\gamma} = 1.7 \times 10^{-3}m^3$.

The resulting work done by the expanding gas

$$w = p_1 v_1^{\gamma}\,[\,v_2^{1-\gamma} - v_1^{1-\gamma}]/(1 - \gamma),$$

$$= 101.5\ J.$$

If we take the "very simple" approximation of considering the curve in Figure A25 as a straight line, then we find the shaded area to be

$$(v_2 - v_1)(p_1 + p_2)/2 = 108\ J.$$

Similarly, for a balloon, the work done in expanding from 2.5 kPa above atmospheric to atmospheric pressure is provided by the following data:

$p_1$ = 105,400Pa; p2 = 103,000Pa;

$v_1 = 6.4 \times 10^{-3}m^3$; $v_2 = (p_1 v_1^{\gamma} / p_2)^{-\gamma} = 6.5 \times 10^{-3}m^3$.

The resulting work done by the expanding gas

$$w = p_1 v_1^{\gamma}\,[\,v_2^{1-\gamma} - v_1^{1-\gamma}]/(1 - \gamma) = 12\ J.$$

We can also examine the behaviour of air as a spring by considering a simple experiment using a piston and cylinder arrangement shown schematically in Figure

A26. The air in the cylinder is initially compressed to $p_1$ and then the piston is moved to compress the air further by decreasing the volume of the contained air. Consider the length of the initial volume to be L and the compression to be (say) $\Delta L$, the area of the piston remaining constant at A.

The increase in force on the piston may be calculated by assuming that the compression is adiabatic. This means that no heat is either absorbed or released by the gas during compression. This is a fair assumption if the compression is small and occurs rapidly.

$F_1 = p_1 \times A;\ v_1 = A \times L;\ v2 = A \times (L - \Delta L).$

$p_2 = (p_1 v_1^{\gamma} / v_2^{\gamma}) = p_1 [\, L/(L - \Delta L)]^{\gamma}.$

$F_2 = p_2 \times A.$

$k = (F_2 - F_1)/\Delta L.$ (k is the spring constant or elastic modulus of the air spring) $= A \times p_1 [\, 1/(1 - \Delta L/L)^{\gamma}]/\Delta L.$

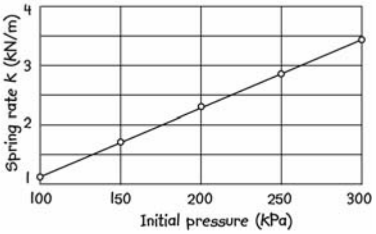

Figure A27 Air as a spring based on the operating arrangement shown in Figure A26

As a result of this expression for the spring constant k of an air spring, the value of k will be a function of the initial pressure in the spring. In this way air, or gas, springs may be modified during operation by increasing or decreasing the pressure within the spring. In some automobiles this effect is used as a means of providing variable rate suspension systems. For L = 100 mm, $\Delta L$ = 10 mm and A = 100 $mm^2$, the spring constant is plotted against initial pressure $p_1$ in Figure A27. Clearly, as expected from the equation for k, and indicated in Figure A27, air-spring behaviour is quite linear for small displacements.

## A1.4 NEWTON OR ARISTOTLE?

Our understanding of the way mechanics operated in our universe, based on Newton's Laws, has remained virtually unchallenged for nearly 300 years. The Newtonian view of mechanics still remains quite appropriate for most situations, other than those involving speeds close to the speed of light. According to Newton (who, according to Stephen Hawking, was not a very nice man[A8]), bodies moving at constant speed have all the forces acting on them in perfect equilibrium. Moreover, constant acceleration of a body requires a constant (unchanging) force to act on it. Now, these ideas seem relatively easy to understand in simple situations. Surprisingly, these same relatively simple ideas can cause some head-scratching, when introduced into not-so-easy situations. For a considerable time before Newton, the Aristotelian view of the universe of mechanics tended to confuse the concepts of speed and acceleration. Aristotle claimed that the speed of a body at constant acceleration would depend on its mass.[A9] It is interesting to speculate on how students of mechanics would deal with

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[A8] Hawking (1998).

[A9] See the reference to Galileo's experiments on falling masses in Sobel, (2000).

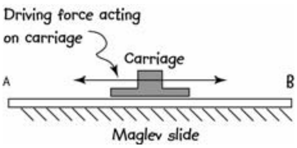

Figure AE1. Maglev test track

less than simple situations, where Newton's Laws should be invoked. Studies of some responses by students, including some university-level participants, by COLOS,[A10] has found that, when faced with these "less than simple" situations, many first-time students of mechanics appear to intuitively adopt the Aristotelian view in favour of the Newtonian view. The following exercises explore the depth of understanding that students have attained in Newtonian mechanics.

AE1. A new type of train is based on the "maglev" principle of floating the carriages on rails using magnetic levitation.[A11] Figure AE1 shows a schematic sketch of a rail carriage floating on a length of test track. The following are some questions facing designers of this new form of transport. The conditions of interest to engineers are as follows:

1. F towards B unchanging; 2. F towards B increasing; 3. F towards B decreasing; 4. F towards A unchanging; 5. F towards A increasing; 6. F towards A decreasing; 7. F zero.

Considering that the speeds of the carriage are of order 200 kph (kilometre per hour) and friction and air resistance may be neglected, what will be the speed and acceleration of the carriage (towards A,B, increasing, decreasing, constant) under the seven conditions described?

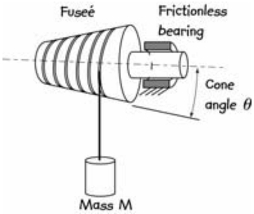

Figure AE2. A new type of fusée

AE2. The fusée, a conical pulley device (similar to that in Figure AE2), was already known to watchmakers in the fifteenth century. It was a device used in mass-driven clocks to equalise the clock spring as it wound down. Although it was a simple device, its main design failing came from the inescapable stretching of the string attaching the mass to the fusée. In modern clocks the fusée was replaced by much more complicated escapement mechanisms. A new invention proposes to use Kevlar or glass fibre strings in a fusée (with virtually zero stretch). It is being tested in a vacuum and friction in the supporting bearing may be neglected. Considering the cone angle $\theta$ as the main design variable, the conditions of interest to the designers are:

1. $\theta$ positive (as indicated in the figure); 2. $\theta$ negative (the cone increases in diameter away from the bearing); 3. $\theta$ zero (uniform diameter fusée).

For each case what will be the angular speed of the fusée (increasing, decreasing or constant)?

AE3. A mass M is attached to a string and rotated overhead with the axis of rotation vertical. If the string breaks suddenly, what will be the path of the mass M once released?

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[A10] Härtel (1994); White (1983).

[A11] See www.maglev2004.cn, the official site for the eighteenth *International Conference on Maglev and Linear Drives*, held in Shanghai, PRC, October, 2004.

# APPENDIX A2

# UNITS OF MEASUREMENT AND CONVERSION FACTORS

> *In Xanadu did Kublai Khan*
> *a stately pleasure-dome decree,*
> *where Alph, the sacred river, ran*
> *through caverns measureless to man*
> *down to a sunless sea,*
> *so twice five miles of fertile ground*
> *with walls and towers were girdled round…*
> Samuel Coleridge Taylor 1798

To the inexperienced, though inventive designer, the idea of units of measure may seem unnecessarily pedantic in the context of make-and-test projects. The substantive argument for considering units, and (shock, horror!) conversions between units, is that they form part of the formal engineering language that permits communication between problem specifier and problem solver. In addition, the history of units and their adoption by various institutions and countries provides a fascinating and often illuminating insight into human nature "in the large".

Although difficult to prove, it is likely that even early cavemen used units of measure for exchange (*e.g.*, "my cave is the height of two Triceratops" – about 4 metres, or "I wish to trade five spears of the length of a tyrannosaurus skull" – approximately 1.5 metre). It is certainly true that the compilers of the Old Testament used units of measure as in the case of God instructing Noah *(Genesis 6)*

> 14 *Make thee an ark of gopher wood; rooms shalt thou make in the ark, and shalt pitch it within and without with pitch.*
>
> 15 *And this is the fashion which thou shalt make it of: The length of the ark shall be three hundred cubits, the breadth of it fifty cubits, and the height of it thirty cubits.*

A cubit is an ancient unit of length measure used throughout the Old Testament. It originates as early as 3000 BC (about 5000 years ago), and is the distance from the elbow to the end of the middle finger, approximately 454 – 555 mm. By 2500 BC this had been standardised in a *royal master cubit* of about 520 mm. This cubit was divided into 28 *digits* (roughly the width of a finger) which could be further subdivided into fractional parts, the smallest of these being only just over a millimetre.

Early measurements would make use of "natural measures" as in the surveyor's *rod* or *chain*, the grain merchants *bushel* or the precious stone measure of *carat*. The last is derived from the *carob* seeds used in the trading of precious stones, now standardised as 200 mg.

## Systems of Measurement and Standardisation[A2.1]

Initially the main types of measures were for *lengths* (distances), *areas* (for example, measuring parcels of land or quantities of cloth), *volumes* (for example, measuring quantities of fluids or grains), *mass* and *time*. As technology changed, other units of measure became necessary, including *temperature*, *heat*, *electric current* or *electric potential* and *illumination* level.

In England units of measurement became standardised in the thirteenth century, though variations (and abuses) continued until long after that. For example, up until 1824 there were three different *gallons* (ale, wine and corn) when the UK gallon, still in current use, was standardised at approximately 277 cubic inches (4.545 litres in SI units).

Initially the United States adopted the English system of weights and measures, with a few minor differences. For instance, the wine-gallon of 231 cubic inches was used instead of the English one of 277 cubic inches. The UK *inch* measured 2.53998 cm whereas the US inch was 2.540005 cm. Both were standardised at 25.4 mm in July 1959.

In France the metric system officially started in June 1799. The unit of length was the metre which was defined as being one ten-millionth part of a quarter of the earth's circumference. The production of this standard required a very careful survey to be done which took several years. To permit proper standardisation of measurements and units the *Bureau International des Poids et Mesures* (BIPM) was set up by the *Convention of the Metre* and has its headquarters near Paris, France.

The *Convention of the Metre*, signed in Paris in 1875 by representatives of seventeen nations and modified slightly in 1921, is a diplomatic treaty which gives authority to the General Conference on Weights and Measures (*Conférence Générale des Poids et Mesures*, CGPM), the International Committee for Weights and Measures and the International Bureau of Weights and Measures to act in matters of world metrology, particularly concerning the demand for measurement standards of ever increasing accuracy, range and diversity, and the need to demonstrate equivalence between national measurement standards.

The Bureau's mandate is to provide the basis for a single coherent system of measurements throughout the world, traceable to the International System of Units (SI). This task takes many forms, from direct dissemination of units (as in the case of mass and time) to coordination through international comparisons of national measurement standards (as in length, electricity, radiometry and ionising radiation).

In all the BIPM recognises seven basic units of measure under the International System of Units, *Système International d'unités*, or SI system, and all other measures and units are derived from these.

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[A2.1] Source: *www.bipm.org*: a wonderful SI brochure is freely available from this site. See also http://*physics.nist.gov/cuu/index.html* for the USA version of standard system of units.

## The Seven Fundamental SI Units

- *Length* – The *metre* (m) is the length of the path travelled by light in vacuum during a time interval of 1/299,792,458 of a second.
- Mass – The kilogram (kg) is the unit of mass; it is equal to the mass of the international prototype of the kilogram.
- *Time* – The second (s) is the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom.
- *Electric current* – The *ampere* (A) is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 m apart in vacuum, would produce between these conductors a force equal to $2 \times 10^{-7}$ Newton per metre of length.
- *Temperature* – The *Kelvin* (K) unit of thermodynamic temperature is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.
- *Quantity of elemental material* – The *mole* is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12. When the mole is used, the elementary entities must be specified and may be *atoms*, *molecules*, *ions*, *electrons*, other particles or specified groups of such particles.
- *Luminous intensity* – The *candela* (cd) is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency $540 \times 10^{12}$ Hertz and that has a radiant intensity in that direction of 1/683 Watt per steradian.

## Some Derived Units and Dimensions

All units of measuring physical quantities may be derived from these seven fundamental units. Table A2.1 lists some of the derived units and their symbols. *Area*, *density*, *force* and *pressure* are typical derived units. The SI agreed format for all the units and their symbols is in the singular. Typically, ten metre (10 m), or ten kilogram (10 kg), rather than ten metres, or ten kilogrammes. In addition, each quantity has associated *dimensions* in mass (M), length (L) and time (T). These dimensions permit the evaluation of relationships between derived units. Table A2.1 lists the dimension for all the derived units. As an example, the unit of force is Newton, derived by the definition that it is the *force* required to *accelerate* a *mass* of one kilogram at one metre per second per second (invoking Newton's law, $F = Ma$). Its dimensions then become $[MLT^{-2}]$. *Work* is the quantity derived from the definition

Table A2.1 Derived quantities and their dimensions

| Quantity | Unit | Symbol | Dimensions |
|---|---|---|---|
| Area | Square metre | $m^2$ | $L^2$ |
| Volume | Cubic metre | $m^3$ | $L^3$ |
| Velocity (speed) | Metre per second | $m\ s^{-1}$ | $LS^{-1}$ |
| Acceleration | Metre per second per second | $m\ s^{-2}$ | $LS^{-2}$ |
| Density | Kilogram per cubic metre | $kg\ m^{-3}$ | $ML^{-3}$ |
| Concentration | Mole per cubic metre | $mol\ m^{-3}$ | $ML^{-3}$ |
| Specific volume | Cubic metre per kilogram | $m^3\ kg^{-1}$ | $L^3M^{-1}$ |
| Current density | Amperes per square metre | $A\ m^{-2}$ | $A\ L^{-2}$ |
| Force | Newton | N | $MLT^{-2}$ |
| Work | joule | J | $ML^2T^{-2}$ |
| Power (rate of working) | Watt (joule/second) | W | $ML^2T^{-3}$ |
| Pressure | Newton per square metre, or Pascal | Pa | $ML^{-1}T^{-2}$ |
| Stress | Newton per square metre, or Pascal | Pa | $ML^{-1}T^{-2}$ |

that *one unit of work is performed* by *one Newton force* moving *one metre*. Hence the units of work are $[ML^2T^{-2}]$ (*i.e.*, force x length). Kinetic energy is the energy of a moving body of mass $m$ at velocity $v$. Hence $KE = mv^2/2$. The dimensions of $KE$ are $[ML^2T^{-2}]$, or the same as the dimensions for *work*. Clearly, these two derived quantities, *work* and *energy*, have the same dimensions and indeed they are measured in the same units of joule (*J*).

The dimensions of units also permit the easy interchange between different sets of units. As an example consider the quantity stress expressed in the old civil engineering unit of *kip* (kilo pound per square inch) to be converted to the SI unit of Pascal (Pa = Newton/m$^2$).

1 pound force = 0.454 kg x 9.8 (the gravitational constant) N,

1 inch = .0254 m,

$$\frac{1000\ \text{lb}}{\text{in}^2}\left[\frac{[MLT^{-2}]}{[L^2]}\right] = \frac{0.454(\text{kg}/\text{lb})\times 9.8\ \ (\text{gravitational}\bullet\text{acc}^{\text{n}}.)}{.0254^2(\text{metre}^2\ /\ \text{inch}^2)}$$

$$= 6894\ \ \text{kPa}\left[\frac{[MLT^{-2}]}{[L^2]}\right].$$

*Table A2.2. Prefixes used to denote orders of magnitude in units*

| *Prefix* | *Symbol* | *Power of ten* |
|---|---|---|
| *yotta* | *Y* | *24* |
| *zetta* | *Z* | *21* |
| *exa* | *E* | *18* |
| *peta* | *P* | *15* |
| *tera* | *T* | *12* |
| *giga* | *G* | *9* |
| *mega* | *M* | *6* |
| *kilo* | *k* | *3* |
| *hecto*[1] | *h* | *2* |
| *deca*[1] | *da* | *1* |
| | | *0 ($10^0 = 1$)* |
| *deci*[1] | *d* | *-1* |
| *centi*[1] | *c* | *-2* |
| *milli* | *m* | *-3* |
| *micro* | $\mu$ | *-6* |
| *nano* | *n* | *-9* |
| *pico* | *p* | *-12* |
| *femto* | *f* | *-15* |
| *atto* | *a* | *-18* |
| *zepto* | *z* | *-21* |
| *yocto* | *y* | *-24* |

Note 1. These prefixes are not recommend by SI and are included because they are still in use by some systems of units.

In many situations there is a need to express quantities in very large or very small units. The SI system recommends standard prefixes for denoting various orders of 10 as the multiplier of the basic unit. For example, one kilowatt, denoted kW is 1000 W. Table A2.2 lists the standard prefix set recommended by SI, virtually all prefixes differing by three orders of magnitude (*i.e.*, Giga is three orders of magnitude larger than mega and pico is three orders of magnitude smaller than nano).

There are some important units used internationally that have not yielded to SI standardisation. The following are some examples:

- *knot* = 1 nautical mile per hour = (1852/3600) m/s; The nautical mile is a special unit employed for marine and aerial navigation to express distance. The conventional value given above was adopted by the First International Extraordinary Hydrographic Conference, Monaco, 1929, under the name “International nautical mile”. As yet there is no internationally agreed symbol. This unit was originally chosen because one nautical mile on the surface of the Earth subtends approximately one minute of angle at the centre.
- *are* = 100 m$^2$, a unit still in common use in the form *hectare*, short for *hecto-are* or 10$^4$ m$^2$.

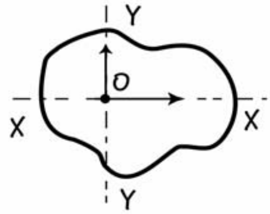
- *bar* – as a unit of pressure, approximately in multiples of standard atmospheric pressure (*atmospheres* as measured by a *barometer* – hence *bar*). 1 bar = 0.1 MPa = 100 kPa = 1000 hPa = $10^5$ Pa.
- *yard* – still used in expressing distances (a mile = 1760 yard); 1 yard = 0.9144 metre; same in the US and UK.
- *pound* – for measuring quantity of substances = 0.453 592 37 kilogram; same in the US and UK.
- *US gallon* (liquid) – volumetric measure = 3.785,411,784 litre.
- *UK gallon* = 4.546,09 litre; different from US gallon.
- *Ton* – a unit of mass = 2000 pound (*short ton*) in US and 2240 pound (*long ton*) in UK.
- Note that the SI unit of megagram (Mg = $10^6$ gm) is the *Tonne*.
- The international unit of thermal energy is the calorie (cal) 1 cal = 9.80,665 joule.
- The speed of light in vacuum = 299,752,458 $ms^{-1}$.
- Acceleration due to gravity = 9.806,65 $ms^{-2}$.
- Newton's gravitational constant G = 6.674,2E-11 $m^3kg^{-1}s^{-2}$.

## Conversion Factors

| Quantity | SI unit | To get (other unit) | Multiply SI unit by |
|---|---|---|---|
| Mass | kg | pound (lb) | 2.204 62 |
| | | ounce (oz) | 35.274 0 |
| Length | metre | foot (1/3 yard) | 3.280 84 |
| | | inch (1/12 foot) | 39.370 1 |
| | kilometre (km) | mile (5280 ft) | 0.621 37 |
| Volume | litre (l)(=E-03 $m^3$) | gallon US | 0.264 172 |
| | | gallon UK | 0.219 969 |
| | | cubic foot ($ft^3$) | 3.5315E-02 |
| Density | kilogram/metre$^3$ (kg $m^{-3}$) | pond/cubic foot (lb $ft^{-3}$) | 6.242 8E-02 |
| Force | Newton (N) | pound force (lbf) | 0.224 809 |
| Moment | Newton metre (Nm) | foot pound force(ft lbf) | 0.737 562 |
| Pressure/stress | Pascal (Pa = N $m^{-2}$) | pound force/in$^2$ (psi) | 1.450 4E-04 |
| | | pound force/ft$^2$(psf) | 2.088 5E-02 |
| | | bar | 1 E-05 |
| | | millimetre Mercury (mm Hg) | 7.500 6E-03 |
| | | inch water (in $H_2O$) | 4.014 6E-03 |
| | Tonne/metre$^2$ ($Tm^{-2}$) | UK Ton/ft$^2$ | 9.143 789E-05 |
| | | US Ton/ft$^2$ | 1.024104E-04 |
| | bar | Atmosphere (atm) | 0.986 923 |
| Work/energy | joule (J) | British thermal unit (BTU) | 9.478 2E-04 |
| | | Calorific heat unit (CHU) | 5.2657E-04 |
| Power | Watt ($Js^{-1}$) | Horse power (Hp) | 1.341 0E-03 |

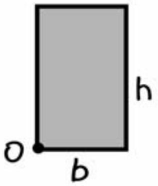
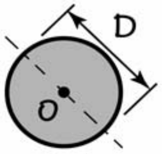
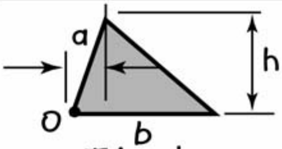
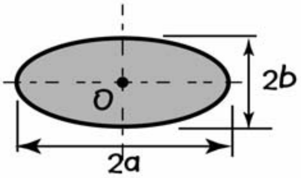
# APPENDIX A3

## SOME PROPERTIES OF PLANE SECTIONS AND ANSWERS TO SELECTED EXERCISES



Two relationships of importance are:

Polar 2nd moment of area Ip = $I_{xx} + I_{yy}$, and the Parallel Axis Theorem, $I_z = I_w + Ah^2$, where $I_z$ is the second moment about axis ZZ, $I_w$ is second moment about axis WW, with ZZ and WW parallel and h is the distance between them.

| Shape | Area | Centroid | | $I_{xx}$ | $I_{yy}$ |
|---|---|---|---|---|---|
| | | $O_x$ | $O_y$ | | |
|  <br>Rectangle | bh | b/2 | h/2 | $\frac{bh^3}{3}$ | $\frac{b^3h}{3}$ |
|  <br>Circle | $\frac{\pi D^2}{4}$ | 0 | 0 | $\frac{\pi D^4}{64}$ | $\frac{\pi D^4}{64}$ |
|  <br>Triangle | bh/2<br>= A | $\frac{(a+b)}{3}$ | h/3 | $Ah^2/18$ | $A[b^2 - ab + a^2]/18$ |
|  <br>Ellipse | $\pi ab$ | 0 | 0 | $\frac{\pi ab^3}{4}$ | $\frac{\pi ba^3}{4}$ |

# ANSWERS TO SELECTED EXERCISES

*Doubt is not a pleasant condition, but certainty is absurd.*
Voltaire
*Everything should be made as simple as possible, but not simpler.*
Einstein

### E2.1 Newton's bucket

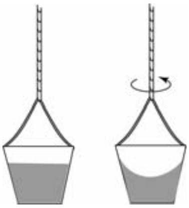


Figure A3.1 Newton's Bucket Experiment

A simple experiment, conducted by Newton, involves somewhat mysterious results. Figure A3.1 shows a bucket which contains water and is suspended by a cord so it is free to rotate around its centreline. The bucket has been turned many revolutions around the centreline so the cord is twisted and exerts a torque on the bucket. The surface of the water is flat before the bucket commences to rotate under the action of this torque and when the bucket is held motionless relative to Earth.

When the bucket is permitted to rotate as the twisted rope unwinds, the water gradually recedes from the middle of the bucket and rises up at the sides of the bucket creating a concave (parabolic) surface as indicated in the figure. Newton's experiment with the rotating vessel of water informs us that even though we do not exert any rotational forces on the body of water (as we would on a mass connected to a string rotating about a centreline), it still experiences centrifugal forces in the Earth's gravitational field. The motion is understood in fluid mechanics as a"free vortex".

### E2.2 Einstein's Elevator

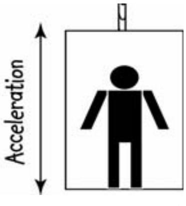


Figure A3.2 Einstein's Elevator

Einstein realised that frames of reference and relative motion are vital concepts. He conducted a thought experiment in which he considered a person in an elevator while the elevator's acceleration was up, down or zero. The effect on the person in the elevator (the observer) was the apparent increase or decrease in mass in spite of there being no change in real mass of the person. If the elevator reaches 9.81 $ms^{-2}$ downward, the observer will appear to be weightless.

### E2.3 Schrödinger's Cat

Erwin Schrödinger (1887–1961) was a quantum physicist who used the cat example as an illustration of uncertainty in quantum mechanics. He proposed in 1935 a demonstration of the apparent conflict between what quantum theory tells us is true about the nature and behaviour of matter on the microscopic level and what we observe to be true about the nature and behaviour of matter on the macroscopic level.

First, we have a living cat and place it in a thick lead box. At this stage, there is no question that the cat is alive. We then throw in a vial of cyanide and seal the box. We do not know if the cat is alive or if it has broken the cyanide capsule and died. Because we have no way of knowing if the cat is alive or dead, the uncertainty of its state renders it to be in both states at once until we open the box and discover its actual state.

E2.4 The Bicycle Riders

Analogous to this problem is that of the bicycle riders who start from two towns 40 km apart at exactly the same time riding towards each other. Their average speed is 5 kph. A fly lands on Cyclist 1 just as he commences the ride, who flicks at the fly which in turn takes off in the same direction as the cyclist. Because the flying speed of the fly is greater than the speed of the cyclist it is able to meet the advancing Cyclist 2. Then the fly returns to Cyclist 1, continuing to oscillate between the two cyclists until the two meet. If the flying speed of the fly is 10 kph, how far has it travelled in this process? Clearly, the cyclists meet (on average) in 4 hours from the start (halfway between the two towns) and the fly flies for 4 hours at 10 kph. Hence the distance it covers is 40 km. There is an alternate (long-winded) solution involving an infinite series of distances travelled by the fly.

An amusing story about this analogous problem is one involving John von Neumann (1903–1957), the inventor of the stored program computer. von Neumann was a child prodigy who at age six could divide eight-digit numbers in his head. While at MIT a young colleague posed the bicycle problem to him. von Neumann almost immediately gave the answer. The crestfallen colleague remarked "Ah, you have heard this problem before." "No," said von Neumann, "I simply summed the infinite series."

E2.5 Consider a chess or checkerboard with black and white squares. The opposite two corners of such a board are both the same colour (let us say black). If the covering tile is also in two colours, it will be clearly unable to cover all the squares, because of the 64 board squares there remain 30 black and 32 white squares. Hence if we eliminate all the black-white pairings, eventually there will be a need for a covering tile with two white squares.

E2.6 Approximately 2 minutes per day in error, also represents an error of 8,860 km. The cesium clock can locate objects to within 1 in 3 x $10^8$.

E3.3 Nine dots and six matches.

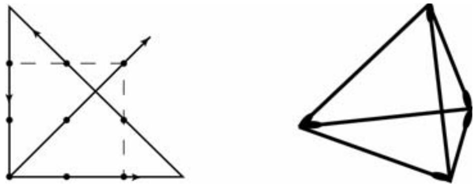


Figure A 3.3 The Nine Dots and the Six Matches solution

The nine dots and the six matches problems illustrate the nature of delimitation in solving puzzles and problems. Here the solutions really represent cases of "thinking outside the square".

E3.5 Marbles in a bag

Number the bags from 1 to 10 and take one marble from bag 1, two from bag 2 three from bag 3, and so on. If the 9 gram marbles are in bag N then the total mass will be 10 + 20 + 30 +... 9N +... = (500 – N) gm.

E6.1 The specific heat of water (Cp) is 1 Calorie gm-1 degree-1. If the temperature of the cup of tea is (say) 80°C, that makes it about 60°C above the average room temperature. If we could recover the whole of this thermal energy from the cup of tea then we could write

$$m.C_p.\Delta T = m.g.h, \text{ or } 1000 \times 60 \times 4.187 = 9.81\ h$$

$$h = 4.187 \times 1000 \times 60/9.81 = 26\ \text{km!}$$

An amusing party trick (among a collection of engineers) is to ask some engineer this question and ask someone to "guess" the result.

# INDEX