EXTRAITS

Thinking in Physics

The pleasure of reasoning and understanding

Laurence Viennot

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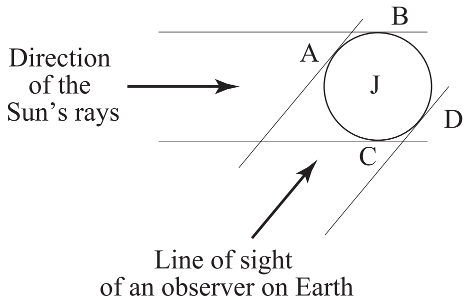


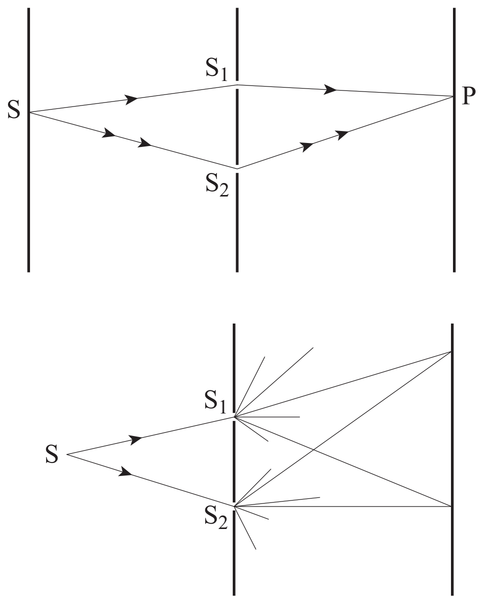
Typical student interpretations: The slanting arrow seems to be interpreted as a ray (visual?):

– The rays from Earth cross the rays from the Sun (Year 11).

– CD and AB are both in shade (Year 11).

Suggestion: Avoid using the same symbols for rays and line of sight.

Figure 1.2 - *This figure is intended to explain the visibility of Io, one of Jupiter's satellites.*[16]



Typical student interpretation: The light may have "deviated": Each emerging path may be the unique continuation of the corresponding incident ray.

– The light has deviated (Year 11).

– The light has deviated (blanked out). The light cannot follow these paths (Year 13).

Ideas to work on: What happens at the holes is a diffraction phenomenon.

Suggestion for a less ambiguous drawing: This diagram suggests the phenomenon of diffraction, and shows how to analyse the illumination of the screen at various points. This involves selecting the relevant light paths for each point on the screen (backward selection).

Figure 1.3 - *Principle of interference using* Young*'s holes*
*(*S*: point source of light,* S_1, S_2*: holes in the first screen, P: detector).*

16 Very simplified version of an image shown in Botinelli L., Brahic A., Gouguenheim L., Ripert J. & Sert J. (1993) *La Terre et l'Univers*, Hachette, Paris, p. 121.

ask what happens if the source of the signal is more powerful–if the string is struck "harder" or someone shouts louder: a good proportion of people questioned[27] predict that the disturbance will propagate faster. And this, despite the fact that the commonly taught formulation (*i.e.* the speed depends only on the medium) is well known to them. What is certain is that they just have not fully realised what this means *i.e.* a surprising thing: that propagation speed is independent of the power of the source.

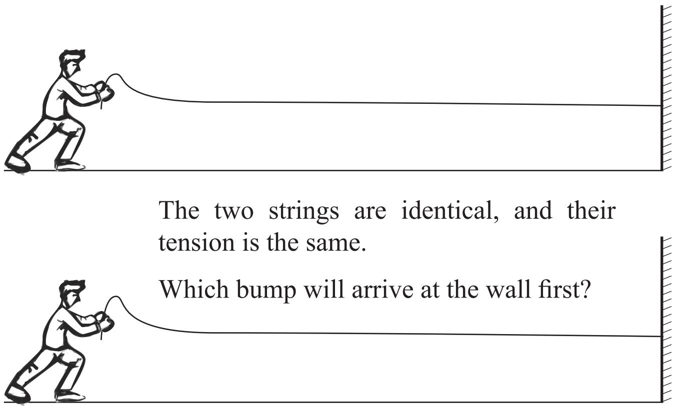


Figure 2.1 *- A situation which underlines the meaning of a well-known statement: "for a stretched string, the speed of propagation of a disturbance depends only on the mass per unit length and the tension". In this model, the race between the disturbances is a foregone conclusion: it's a dead heat!*

There is some benefit to be gained from such knowledge, *i.e.* the ritual statement that propagation speed depends only on the medium, since it implies that this surprising invariance will be questioned by some, or emphasised for others. It is surprises and unexpected phenomena of this kind which illustrate how physical theories are not just a familiar collection of analyses of situations we know how to handle; they have great unifying power for specific cases that we might have thought distinct, but which in fact, from certain points of view, prove to be otherwise.

Sometimes, the merest hint of an explanation is sufficient to induce these welcome surprises, these new and unexpected insights.

2.4 Coefficients of friction

The value of a normal component of contact force F_N and that of its tangential component F_T are coupled by static or dynamic coefficients of friction for two interac-

27 MAURINES L. Spontaneous reasoning on the propagation of visible mechanical signals, *International Journal of Science Education*, 14 (**3**) 279-293; VIENNOT L. (2001) *Reasoning in Physics - The part of common sense*, Dordrecht: Kluwer Ac. Pub., 143-144. See also WITTMANN M.C. (1998) *Making Sense of How Students Come to an Understanding of Physics: An Example from Mechanical Waves*, Unpublished Ph.D. dissertation, University of Maryland; WITTMANN M.C., REDISH E.F. & STEINBERG R.N. (2003) Understanding and Addressing Student Reasoning about Sound, *International Journal of Science Education,* **25**: 8, 991-1013.

ting surfaces. In standard elementary courses on friction,[28] the coefficient μ_s enables the maximum allowable value of the tangential component without slipping to be calculated: $F_T \leq \mu_s F_N$ and the coefficient μ_d enables the value of the tangential component, once slipping has started, to be found: $F_T = \mu_d F_N$. For a rectangular block of mass m sliding on an inclined plane (at an angle θ to the horizontal), the written notation of the balance of forces and the fundamental principle of dynamics (air friction being "negligible") gives the value for tangential acceleration (axis downwards): $a = g\ (sin\theta - \mu_d\ cos\theta)$.

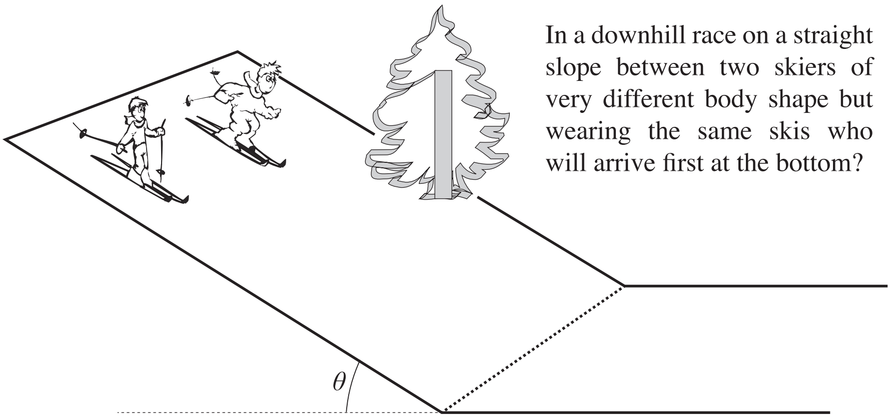


***Figure 2.2** - A situation which underlines the meaning of the standard solution to an exercise involving friction:* "*the acceleration of a skier along the path of steepest descent is: $a = g(sin\theta - \mu_d\ cos\theta)$*", *where μ_d is the coefficient of sliding friction and g is the acceleration due to gravity. According to this model, the race between the skiers is a foregone conclusion: dead heat. Why is this so improbable?*

Let us imagine (this might be a first year university exam question) that this block represents a model of a skier on the line of steepest descent. There is the solution, presented to a tutorial group.[29] What can we usefully add?

Here's a question: if two skiers, otherwise identical in every respect, have skis of different widths, does the solution above predict anything about their performance? This ski width does not appear in the expression for acceleration, a, but is it not relevant? Or else where is it hiding? In the coefficient μ_d perhaps? Otherwise we simply have to resign ourselves to the fact that the solution to this exercise predicts the simultaneous arrival of these two skiers on skis of different widths.

So we come to the question we could so easily have ignored: what exactly **do** these coefficients depend on, and what **don't** they depend on? It's surprising that μ_d and μ_s

28 For more information on the history and limitations of this simple model, read Besson U., Borghi L., De Ambrosis A. & Mascheretti P. (2007) How to teach friction: Experiments and models, *American Journal of Physics*, **75** (12) 1106-1113.

29 See Chapter 4, exercise 4.4.

a solution in which there is separation of each spatial dimension. There we see the power of theory, reduced as it is. Hence we know, with no calculation involved, that a force acting in a single direction ($\overrightarrow{0y}$ for example) will have no effect on the path of a moving object in a direction ($\overrightarrow{0x}$).[41]

Whether these are standard examples or not, this type of conclusion can never be emphasised enough.

3.3 Keeping an eye on a causal reading of relations

Contrary to received wisdom, the inclusion of variables in a relationship does not necessarily correspond simply to a causal analysis of the situation.

Hence the situation Marie CURIE suggested to her young students[42] of a small ball immersed in a bowl of water. Disturbingly, her student Isabelle CHAVANNES' notes state the following:

"*What was exerting pressure on the ball when it was in the water? The water, of course,* ***but also the air, which was itself pressing on the water. This air pressure was transmitted through the water.*** *When the ball was on the surface of the water, only atmospheric pressure was pressing on it; when I pushed it under the water, it had to support* ***both the atmospheric pressure and*** *the pressure of the water.*"

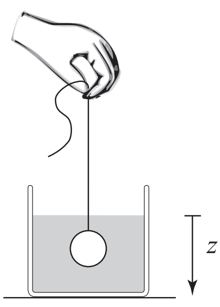


Figure 3.1 *- Small ball immersed in a bowl of water.*

This simple situation can be read in two ways.

- *A causal interpretation of hydrostatic pressure. Marie CURIE's explanation as reported by a student. What was exerting pressure on the ball when it was in the water? The water, of course, but also the air pressing on the water. This pressure is transmitted through the water;*
- *A Newtonian reading of the situation: what was exerting pressure on the ball when it was in the water? The water.*

In the expression $p(z) = p_{atm} + \rho gz$, there are two terms in the expression for p(z), but this variable locally characterises the water and determines its interaction with the ball.

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41 An exercise suggested during a study of French *Terminale* (Year 13) students features this property for a mass spectrometer: does the transit time for a particle of given charge and initial velocity parallel to the plates of a plane capacitor depend on the fact that it is charged or not? Besides the significant number of errors, the students' answers provided interesting food for thought. (RIGAUT M. & VIENNOT L. (2002) Réduire le théorème du centre d'inertie : jusqu'où ? *Bulletin de l'Union des Physiciens,* **841**, 419-426).

42 Collected *Lessons of Marie CURIE*, Isabelle CHAVANNES (1907) *Physique élémentaire pour les enfants de nos amis*. Work coordinated by B. LECLERCQ (2003), EDP Sciences, Paris, p. 33

If the parts in bold fonts of this reasoning are removed, the text is perfectly consistent. On the surface of the ball (submerged to a depth z) the water exerts contact forces due to the pressure determined by the expression $p = p_0 + \rho g z$ (using the usual notation for variables, axis $\overrightarrow{0z}$ directed downwards, and origin at the surface of the water). Even though this expression includes two terms involving atmospheric pressure p_0 and depth of immersion z respectively, it is the water, and only the water, which exerts contact forces on the outside of the ball. A causal reading must not allow the strict meaning of the expression to be forgotten.

At a higher level of competence,[43] there is one case where the relationship disturbingly hides the factor that determines the value of a variable. This is the expression for the electric field $\vec{E}$ in the neighbourhood of a conductor in electrostatic equilibrium: $\vec{E} = \frac{\sigma}{\varepsilon_0}\vec{n}$, where $\vec{n}$ is a unit vector normal to the conductor directed outward to the point under consideration, σ is the local surface charge density and ε_0 is the permittivity of free space (Fig. 3.2).

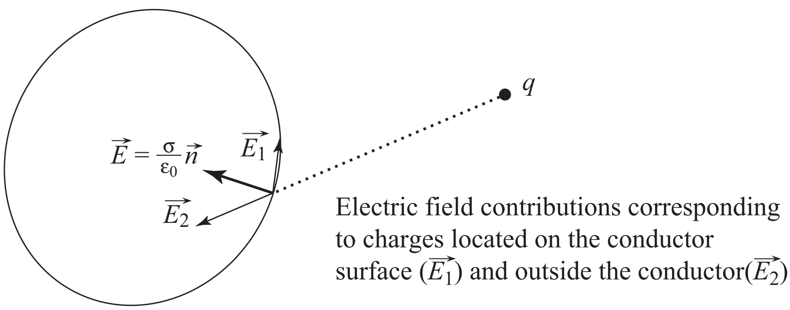

Figure 3.2 *- The electric field in the neighbourhood of a conductor is normal to it. So far as the charge is concerned, the expression mentions only the surface density σ in the neighbourhood of the point being considered, but in fact this field results from the contribution of all charges in the universe (here a single external positive charge is shown, while σ is negative).*

If we ask students what are the sources of this field $\vec{E}$, the overwhelming response is that it's down to the individual charges on the conductor (locally, or over the whole conductor).[44] However, the principle of superposition means that the field at some arbitrary point of some arbitrary configuration is the sum of the contributions from *all* the charges in the universe. Should the only source admissible by the students appear in the formula?[45] Within the variable σ is the cumulative contribution of all the charges present, both outside the conductor and at its surface. The power and

43 Typically in France this would be the second year at university or a preparatory class for entry into a *grande école*, second year.

44 See Viennot L. & Rainson S. (1999) Design and evaluation of a research-based teaching sequence: The superposition of electrics fields. *International Journal of Science Education*, Special issue: Conceptual Development in Science Education (continued), **21** (1) 1-16.

45 In the work of S. Rainson (previous footnote), the “cause in the formula” syndrome is mentioned in this connection.

- if the magnetic field is uniform and the initial velocity is not perpendicular to $\vec{B}$?

– What assumption(s) is/are made in the text which may lead to the assertion that the particle is confined to a plane?

– What is the motion of the particle if $\vec{v}_0$ is parallel to the uniform field $\vec{B}$? Is the path stable?

– The fact that the field $\vec{B}$ is uniform is mentioned several times in this demonstration. Recapitulate where and how.

– Give orders of magnitude for the values of v, B and R for the LHC (Large Hadron Collider at CERN, Geneva)?

4.4 Sliding on an inclined plane

This topic has already been covered in Section 2.4. What follows is a suggestion for the text to be submitted to the students, as it is. Phrases in *italics* are intended for the teacher.

First read (the first part of) this exercise and its answer sheet: the skier, in a customary version

Ski jump

A skier of mass m descends a piste consisting of:

– a rectilinear section AB making an angle θ with the horizontal and of length $AB = L_1$.

– a horizontal rectilinear section BC of length L_2.

Denote the magnitude of gravitational acceleration as g. Assume that there is friction between the skis and the snow: let μ_s and μ_d be the static and dynamic coefficients of friction respectively.

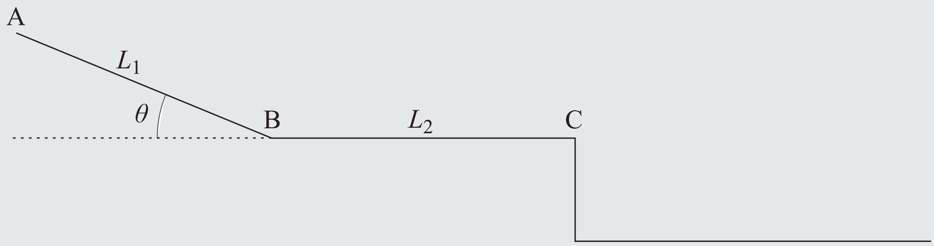

Figure 4.5 - *The elements of a ski slope involved in the ski jump problema*)

a) The skier is at rest on section AB. Draw a diagram showing the forces exerted on the skier. Give the (absolute) value of the frictional force as a function of θ. So that the skier can remain stationary on the slope (without using his ski-poles), θ must be less than a maximum value θ_0. Give an expression for θ_0.

b) Now assume that the angle θ is sufficient for the skis to slide on the snow. The skier starts from A with speed zero at $t = 0$. Determine the skier's acceleration.

c) Choosing an axis $\overrightarrow{0x}$ coincident with AB and with its origin at A, determine the time dependent equation of motion.

d) Let the time taken by the skier to reach point B be t_1. Determine the value of μ_d as a function of g, θ, L_1 and t_1. Give the value of the speed v_1 of the skier at point B as a function of L_1 and t_1.

The teacher's notes include the diagram below and the solution lines which follow. Read this carefully (there are no errors in the calculations).

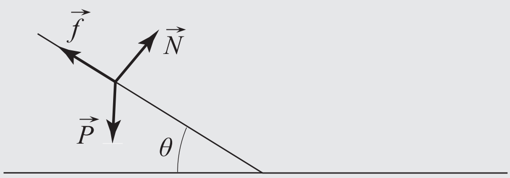

Figure 4.6 *- Diagram for the simplified skier model*

a)
$$f = \| \vec{f} \| = mg \sin\theta$$
$$f < \mu_s\, mg \cos\theta \longrightarrow \theta < \theta_0 \text{ with } \tan\theta_0 = \mu_s$$

b)
$$f = \mu_d\, mg \cos\theta$$
$$ma = mg \sin\theta - \mu_d\, mg \cos\theta$$
$$a = g\,[\sin\theta - \mu_d \cos\theta]$$

c)
$$x = \frac{1}{2} g\,[\sin\theta - \mu_d \cos\theta]\, t^2$$

d)
$$L_1 = \frac{1}{2} g\,[\sin\theta - \mu_d \cos\theta]\, t_1^2$$

hence
$$\mu_d = \frac{1}{\cos}\,[\sin\theta - \frac{2L_1}{g t_1^2}]$$
$$v_1 = a t_1 = g\,[\sin\theta - \mu_d \cos\theta]\, t_1$$

so
$$v_1 = \frac{2L_1}{t_1}$$

Then answer the following questions

What is the sign of g in this text?

Part a):

What does θ mean in the two lines of the "answer" devoted to the static case? Is it:

- the angle at which the skier can get into motion?
- one of the various angles at which sliding can occur?
- one of the various angles at which sliding cannot occur?

Has the variable θ been expressed here in algebraic form?

Parts b), c), d):

Is the motion of the skier

- uniform?
- uniformly accelerating?
- some other case?

Whatever your answer, state to what property of friction, and/or to what assumption, this motion is due.

Luc ALPHAND (triple world downhill champion: 1995, 1996, 1997) begins his descent (under the conditions given in the text) at the same time as a brother of the same physical build (geometrically speaking), but who is much lighter.

Will they arrive at the bottom at same time

- in accordance with the model given here?
- in reality?

Discuss: under what circumstances the mass of the moving object is not involved in the equation(s) of motion (one, or several dimensions respectively)?

Now assumed to be of the same build and weight, Luc ALPHAND and his hypothetical twin begin their descent at the same time under the conditions given in the text. One of them has skis which are twice as wide as the other, but the same length. According to the model given here, will they both arrive at the same time? Whatever your answer, state to what property of friction, and/or to what assumption, this result is due, and discuss.

The validity of the expression found for the acceleration a may be checked by examining the sign of this variable. From zero initial speed, the skier starts his descent and hence the value for a must (at least at the start) be positive downwards, given the choice of orientation for the axis $\overrightarrow{0x}$. Does this impose some particular condition? Discuss. (consider the following experiment: if you

Chapter 6

The relationship between different approaches to the same phenomenon

Under the heading of similar relationships between variables, the previous chapter reconciled some phenomena which appeared at first sight to be different. In a complementary manner, this chapter will go into the theme of links: here we are dealing with a single phenomenon, or context at least, bringing our thoughts together. This will involve different approaches, especially in terms of the scale of the description used: macroscopic, mesoscopic, or even particle-based. Once again, the example will be taken from everyday life and the physics simple.

6.1 An instructional hot-air balloon

With a touch of irony, we can define this "instructional hot-air balloon". For such a balloon, the envelope open at the base defines an internal space of volume V, within which the air is at temperature T_{int} and pressure p_{int}. The whole thing, including passengers, has mass m_{t}. We should simplify, and temporarily forget, for example, the turbulence generated by the burners. Initially, the results will not suffer too greatly, and much will remain understandable. The outside must also be defined: air at atmospheric pressure ($p_{\text{ext}} = p_0$) and at temperature T_{ext}. Very frequently[70], equality of internal and external pressures is added to the model ($p_{\text{int}} = p_{\text{ext}} = p_0$), the rationale being that the envelope is open.

A standard solution relies on ARCHIMEDES' principle: the upthrust due to the outside air on the whole ensemble is balanced by the weight of the volume V of the external air.[71] This weight is yet to be evaluated, as is that of the internal air to balance the forces justifying the equilibrium required. The weights in question, corresponding to the same volume, are subsequently differentiated by different values for the density

70 By way of example: GIANCOLI D.C. (2005) Physics (6th edition): "Instructor Resource Center" CD-ROM, *Prentice Hall.*

71 With respect to this value, neglecting that of the volume of the materials of the gondola and the suspension cords.

of air, itself related to the variables already introduced by the barely transformed ideal gas law: $\rho = \frac{Mp}{RT}$. In three or four lines of working facilitated by the equality of the pressure terms, temperatures (via their reciprocals) and the problem data can all be linked together.[72] We are then in a position to know to what temperature the internal air must be heated to achieve lift-off, and subsequent stability once in the air.

6.2 Ritual: a pact with inconsistency?

Should we be worried about the simplifications inherent in the common approach to this classically presented problem, in particular to first-year university students?

Yes, we should indeed. As we know, physics starts off by thinking of simplifications. However, here we encounter an assumption which, taken at face value, would send the balloon crashing to earth quicker than you could say 'ARCHIMEDES'. If the pressures were the same at every point ("atmospheric pressure"), the resultant of the pressure forces acting on the envelope due to the gases present would be zero. Each part of the envelope would be subjected to two exactly opposite forces. Plus, no particular spatial direction would be preferred by these gases: why should they push upwards? Yet again, using ARCHIMEDES' principle is to make use of the sine qua non of its relevance, namely the existence of pressure gradients, essential for hydrostatic problems where gravity is present. Between the level of the opening and that at the top of the balloon, the pressure of the outside air falls. Ditto for the air inside. However, as this is less dense, the pressure from bottom to top falls less quickly on the inside than on the outside. Starting from a value assumed identical at the level of the opening, the internal and external pressures are not equal elsewhere, in particular at the top of the balloon: the highest pressure is on the inside. We then begin to grasp that the envelope can be inflated and held airborne despite the weight of the whole thing. This analysis is summarised in Figure 6.1 and is illustrated by a strange balloon, cylindrical for reasons of formal economy: there is no need for a complicated integral to show (or even to formally verify) that ARCHIMEDES' principle is consistent with a local analysis of the forces acting on the envelope. The global

72 For a balloon of total mass m_c (for the solid parts), taking account of the density ρ of an ideal gas of (mean) molar mass M, $\rho = \frac{Mp}{RT}$, and from ARCHIMEDES' principle, the Newtonian equilibrium is written: $m_c + \frac{M}{R}\frac{p_{\text{int}}}{T_{\text{int}}}V = \frac{M}{R}\frac{p_{\text{ext}}}{T_{\text{ext}}}V$, *i.e.*, assuming that the (mean) internal and external pressures are very close to their value p_0 at the opening, $[1/T_{\text{ext}} - 1/T_{\text{int}}] = m_c\, R/(p_0 MV)$.

analysis supported by the gradient theorem[73] and its consequence in hydrostatics (the expression for the ARCHIMEDES' interaction) unites the mechanical (local and more direct) balance of forces in play. Two approaches, each casting light on the other, compete for an understanding of the phenomenon. For many students (we will return to this) this was an opportunity to get to the nub of ARCHIMEDES' principle.

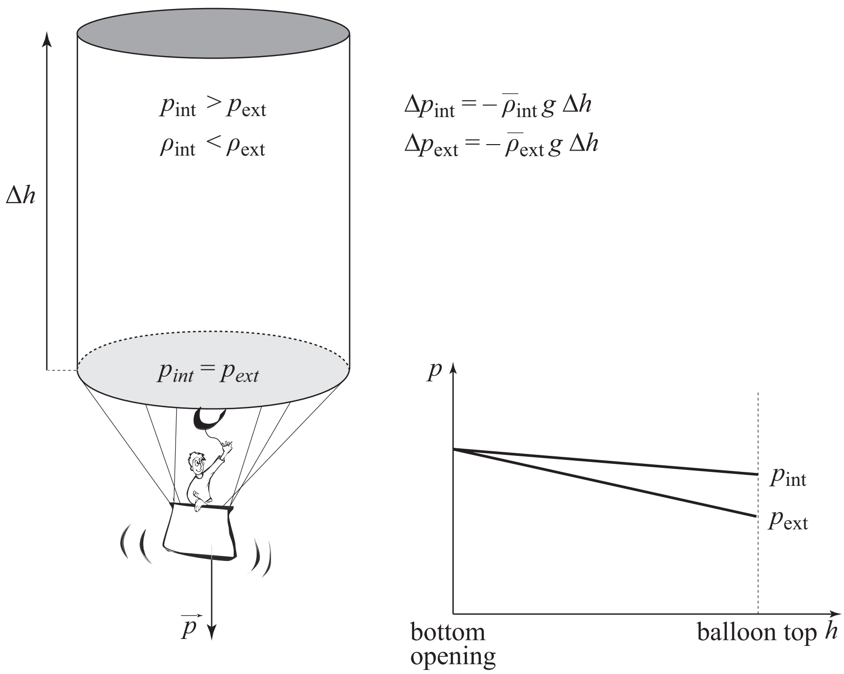

Figure 6.1 *- Elements for understanding how a balloon is held airborne, here shown as a cylinder to facilitate understanding the effect of pressure forces on the envelope (see the text and note 73).*

6.3 Two approaches for a single phenomenon

Let us pause here to consider the unusual nature of this analysis.

Several studies agree as to the reaction of individuals consulted on an exercise containing the assumption in question, namely, that "the pressure is everywhere the same".

73 The gradient theorem, applicable to a closed surface S enclosing a volume V, and (here) to a scalar field p: $\iint_S p\,\overrightarrow{dS} = \iiint_V \overrightarrow{grad\,p}\; dV$; in a fluid of density ρ at equilibrium we have $\overrightarrow{grad\,p} = \rho\,\vec{g}$. ARCHIMEDES' principle follows immediately.
This principle leads to the relation $[1/T_{ext} - 1/T_{int}] = m_c\, R/(p_0 MV)$ (see previous note).
Another approach, here using a cylindrical balloon of height Δh; to first order we have at the upper level: $p_{ext} \approx\ p_0 - \bar{\rho}_{ext}\ g\Delta h$ *et* $p_{int} \approx p_0 - \bar{\rho}_{int}\, g\Delta h$. The supporting force which acts on the upper horizontal face of area S, balances the weight of the solid parts if, and only if, $m_c\, g = (p_{int} - p_{ext})\, S$, which leads to the same expression as that produced by the global treatment $[1/T_{ext} - 1/T_{int}] = m_c\, R/(p_0 MV)$.