# The portable MBL in physics teaching

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**Abstract**

In the last few years a group of members of AIF has developed a series of experimental activities based on the use of on line data acquisition systems, devoted to secondary school and/or university physics teaching. In particular the potentialities have been explored of those so called "portable" systems, i.e. systems that being light, pocket-sized and self-supplied can be operated efficiently also in other environments than traditional labs (ordinary classrooms and open-air environments for field investigations).
In this contribution a selection of the proposals are illustrated, divided into three sections corresponding to different areas of physics (mechanics, thermodynamics and electromagnetism) with the aim of emphasising various aspects of the use of MBL that we think particularly useful in physics teaching.

## Foreword

Using data acquisition systems based on microcomputer (MBL) in physics laboratory offers to the teacher many advantages:
- speed and accuracy in data acquisition
- data recorded in a format easy to be transferred
- speed and easiness in graphic representations
- efficacy in data handling (plots, interpolations, comparisons,...).

These features let us save a lot of time in the laboratory. But time saving and easier experimental work are only the most striking aspects: a closer look shows that on-line the data acquisition systems offer a broader range of didactic advantages. They make easier the comparison between experiments where important parameters are changed, they make available a large variety of data, and make immediately apparent their inter-relations, thus allowing to give physical meaning to the mathematical modelling. Therefore different didactic approaches are made possible for experimental studies of physical phenomena, structured on different levels that may be resumed in the following cycle:

- Qualitative analysis of the phenomenon and identification of its essential features
- Development of a theoretical model
- Design and building the experiment
- Data acquisition and graphic representation
- First level analysis of the graphic representation
- Data fitting with functions suggested by the adopted model
- Calculate interesting variables from raw data and draw corresponding plots
- Analysis of the new graphs and interpolations with functions suggested by the model
- Comparison of the results with the predictions offered by the model
- Study of the possible systematic deviations from theoretical predictions
- Revision of the first model on the basis of the analysis of experimental data
- Design of a new experiment eventually suggested by the modified model
- Back to the first step

In this way the students may be induced to a conscious use of the tools that are typical of physics investigations, and it will be easy to provide them opportunities for the intellectual satisfaction related to find "how things work", which is an essential part of the pleasures that physics may offer.

Moreover the accuracy and abundance of the experimental data made available at "low cost" by MBL, allow to study phenomena without being restricted by an excessive "sterilisation", usually imposed by traditional laboratory (avoid friction, and generally dissipative phenomena.

The large number of accurate data provided at low cost by MBL allows phenomena to be investigated without being forced to "simplify" them as much as it happens in traditional experiments (avoiding friction, being restricted to quasi static processes in order to make measures compatible with human reaction-times, etc.)

This helps to avoid the idea, that usually students develop, that lab experiments are something different from real world events (i.e. just something for the physicists to play with, that makes sense only for them...)

By giving the students an easy way to make measures we allow more room for trying to understand what should be measured and why.

By making possible measurements on even complex phenomena (therefore more similar to everyday life phenomena) MBL helps the students to appreciate also the "fun" of lab activities, a great advantage now that the number of students choosing a scientific career is rapidly decreasing.

In the case one adopts the new technology of graphic calculator (as TI ones) the of PC may be skipped without significant reduction in the quality of experimental performance and data handling. Experiments at secondary school and university introductory levels can be performed in ordinary class rooms: we can bring lab to the students instead of bringing the students to the lab.

Moreover the data handling may be performed by students at home where they may use their PC, having more time to spend without any extra costs for the teaching structure.

With portable MBL (as that provided by CBL-Texas plus TI89 or TI92 or TI83) a sophisticated and costly lab (recently increased by the European standard safety rules) is no more needed for teaching physics.

By using CBL as an *universal measuring instrument* we can drastically cut costs down (reduced to those of a single interface plus sensors) and allow more investments to be made on hardware to set up experiments, while a wider range of experiments is made possible by the reduced time of execution of each of them.

Simply by changing the used probe we transform the measuring instrument from a barometer into a thermometer, or from a voltmeter into a force probe, or from a motion detector into a light probe…and the required procedure to take data remains the same.

CBL not only allows large savings in laboratory instrumental costs, but also offers an important help in science and technology teaching.
Students nowadays see the double-arm scale only in the grand mother loft, and the Bourdon gauge only in the Phys-Lab: in the real world they see only electronic scales and electronic pressure gauges. In the professional world (industry, research labs, etc.) in fact all measuring instruments show the common structure *sensor-interface-microprocessor*. Therefore it is important for the students who will enter this world to have an up to date experience of the instruments they will necessarily use.
Finally even from the point of view of the general scientific education, the use of a data acquisition system, instead of specific measuring instruments, offers to the students the opportunity to more deeply investigate the meaning and the logic of performing measures.
The flexibility of the universal instrument may foster the students' undertaking, and stimulate the bravest among them to design by alone part of the experiments, facilitating a customised teaching that should produce better results.

## 1. Mechanics harmonic and anharmonic oscillations

One of the topics in physics teaching that may take a great advantage from the use of MBL systems (and in particular from the CBL system plus graphic calculators) is the mechanics of oscillatory motions.
This is because in an oscillatory motion it is very important to catch the time evolution of the phenomenon, and the possibility of analysing position, velocity and acceleration plots versus time allows an immediate evaluation of the essential characteristics of each particular type of oscillation.
Even the analysis of the experimental data in less common graphic representations (as velocity vs. position, accelerations vs. position, force vs. acceleration, force vs. position …) may offer precious hints to deepen the student's understanding of the investigated phenomena.
The system sensor-interface-calculator allows to *extend the potentialities of the eye and of the memory* of the student that studies the phenomenon, offering on one side a permanent record of the experimental data for subsequent analysis (even far from the laboratory, where the phenomenon is no more available) and on the other side the possibility of recognising immediately some *qualitative* features of the observed system, by extracting from the graph shape some interesting relations between the variables that characterise the phenomenon. The availability of raw data fully recorded allows to proceed later to a *quantitative* analysis.
To illustrate the potentialities of a qualitative analysis of the data, we consider three oscillating systems: two of them being normally part of introductory courses in mechanics (*mass-spring* and *pendulum*), while the third (an *Atwood machine* with one of the masses dipping into water) is less common but well suited to show the transition from *harmonic* to *anharmonic* behaviour, an aspect often neglected in the traditional laboratory.
In the vertical mass-spring oscillator (if the spring obeys to Hooke's law) is *always strictly harmonic* (i.e. the force is proportional to displacement), in the Atwood oscillator the motion evolves *from anharmonic at large amplitude to harmonic at small amplitude* (the Archimedes' plus the gravitational restoring force switches from a constant value to values proportional to displacement when the mass is partially submerged in water) while in the case of pendulum the *intrinsically anharmonic* motion may be *approximated to harmonic motion* in the limit of *small amplitude*.

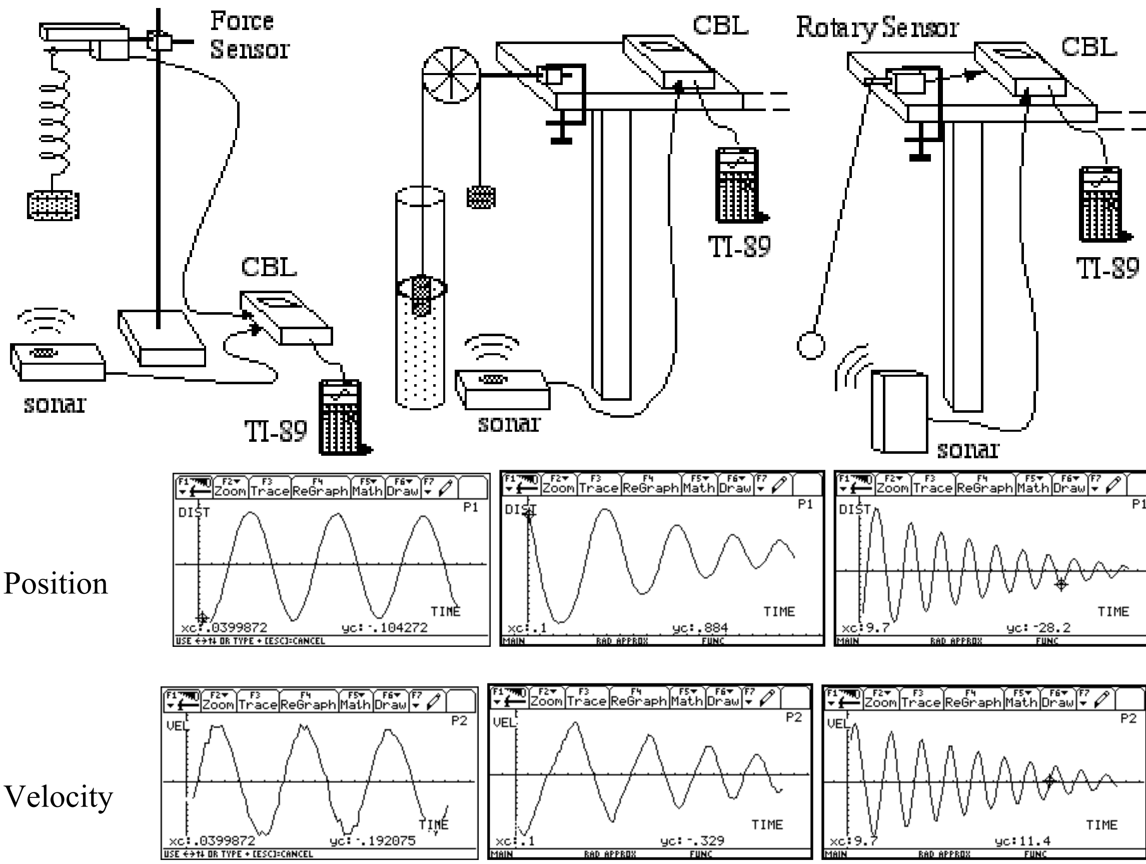
### 1.1 An example of qualitative comparison between oscillators

Contrary to the idea that could be suggested by reading most of the physics textbooks, oscillatory motions of everyday life are rarely harmonic motions. This is due to the fact that the restoring force generating a large fraction of the mechanical free oscillations is the gravitational force which is nearly constant. In some cases a dependence from the position may be present, due to the particular geometry of the system, (as in the case of the circular motion of the pendulum) but in such cases the dependence from displacement is not linear (dependence from the sine of the angle) and it may be approximated to a linear behaviour only for small displacements from equilibrium.

A motion intrinsically harmonic may be produced only in a system where the restoring force is linearly dependent on the displacement of the oscillating body, as in the case of a body attached to a spring where gravity acts only in determining the equilibrium position.

A particular case is that of the buoyancy force (or Archimedes force) which also is due to the gravitational field, that is proportional to the volume of the immersed body and may therefore produce a restoring force proportional to the displacement (i.e. harmonic motion) provided that the oscillating body has constant cross section (e. g. cylinder).

Taking data [1] on the oscillating body position with MBL we may immediately compare qualitatively the motions of the different systems.




Position

Velocity

Mass-spring Atwood Pendulum

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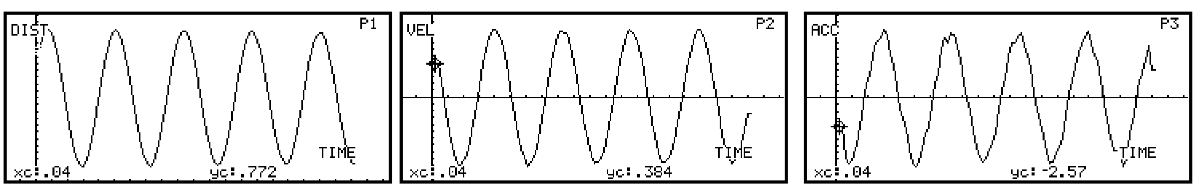
[1] The data here reported were taken using the application Physics from Vernier, in a version modified by G. Delfitto and C. Ragazzini

The position vs. time plots x(t) are quite similar: at first sight they look like sinusoids, more or less damped. However the velocity  vs. time plots v(t) show evident differences in the three oscillators. And the difference is even more evident in the acceleration vs. time plots.
In the mass-spring harmonic oscillator the velocity plot is similar to the position plot, with a phase leading of 90°. In the Atwood oscillator the velocity plot, at large amplitude, is made of straight segments, showing that the motion is uniformly accelerated, with acceleration changing sign at each half-period, while at small amplitude it recall the mass-spring behaviour. Also the large amplitude oscillations of the pendulum is far from sinusoidal: you can’t see it in the x(t) plot, but you’ll see it well in the v(t) plot.
The availability of the *whole data set*, and not only of *few of them* (e.g. those related to gate crossing, as in the traditional laboratory) allows this qualitative but important analysis .
It is therefore possible even in this first analysis to show how the harmonic approximation at small amplitudes is on one hand very useful to make easier the mathematical modelization, but it is on the other hand not adequate to explain in details the behaviour of some phenomena.
Harmonicity implies *isochronism*. A *quantitative* analysis of the plots allows to easily carry out a study of the period versus amplitude.
This approach makes possible to change sequentially different parameters in each experiment, and to observe in real time the agreement or disagreement between the experimental results and the predictions made on the basis of the assumed modelization, and eventually to revise the used model.
In the following we briefly illustrate, for each of the considered oscillators, some possible analyses of the data taken.

## 1.2 The vertical spring-mass oscillator.

The necessary material for a complete study of the vertical spring-mass oscillator is made of: motion detector (Sonar), force sensor, a series of masses with hook, a series of springs.
Once suspended, through a spring, a mass to the force sensor, the sensors are zeroed in equilibrium position. Then the oscillation is started, and position, force, velocity and acceleration are recorded versus time.



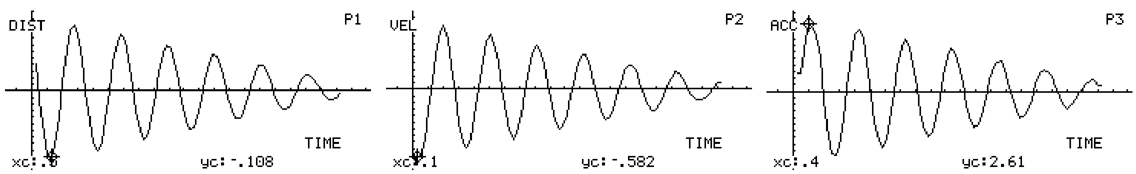

The plots x(t), v(t), a(t), f(t),show clearly a sinusoidal behaviour, as expected for harmonic motion. It may be shown in Data Matrix Editor (electronic spreadsheet in the graphic calculator) how to build functions to fit the different plots, to discuss the phase shifts, and so on. By using the cursor measurements of the period may be taken and it may be shown that period does not depend on amplitude, as expected for harmonic motion (isochronism). The plot f(x) appears linear and from its slope the elastic constant may be derived. The plot a(x) is also linear, and once known the elastic constant, one can obtain from its slope the effective inertial mass of the oscillator, and finally by using different bodies of known masses to derive the effective inertial mass of the spring
In DataMatrix Editor we may build columns with the values of potential energy (gravitational, and elastic) and kinetic energy. By plotting these values versus time or versus position we may discuss energy transformations: a plot of total energy versus time for a long acquisition, or for an oscillation well dumped by a large disc attached to the mass, allows to calculate the friction coefficient. Large

amplitude oscillations show that energy is dissipated in burst, corresponding to the velocity peaks (viscous friction).

## 1.3 The pendulum.

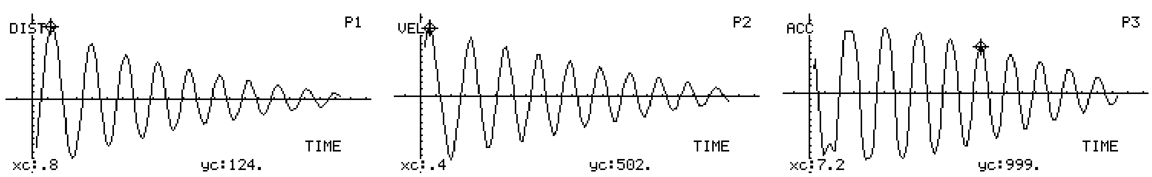
The necessary material for this experiment is: potentiometric rotary sensor, knitting iron, three small rubber balls (one with a hole through), sticking tape.
We pass the knitting iron through the hole in the potentiometer axis and we block it by sticking tape. We slip onto the end of the knitting iron the perforated ball. Sensors are zeroed with the pendulum in equilibrium . We start oscillation and we take data first at large amplitudes (≈±350°) then at small amplitudes (≈±30°). We repeat the experiment after attaching two ball to the first one with sticking tape at the same distance from the pivot. We repeat the experiment after displacing the ball to smaller distance from the pivot.

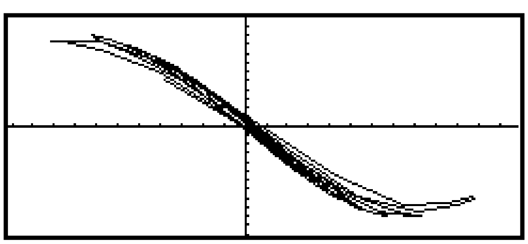
SMALL AMPLITUDES



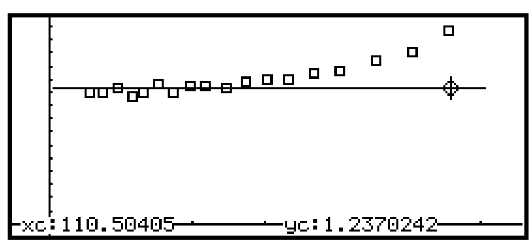

Studying small amplitudes the plots x(t), v(t), a(t) show sinusoidal behaviour, as expected in harmonic motion. Measuring the period at various amplitudes we observe that this motion is isochronous. It may be shown that period does not depend on mass while it does depend on its distance from the centre of oscillation.
The dynamic model may be analysed and the measured period may be compared with the predicted value $T=2\pi\sqrt{L/g}$ .

LARGE AMPLITUDES

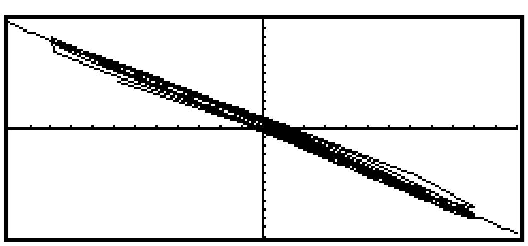


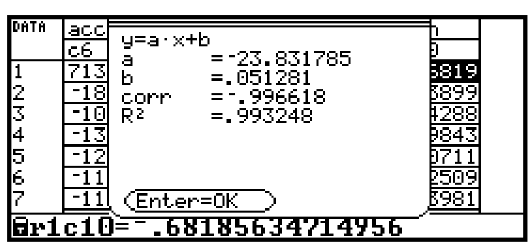



Acceleration (y) vs. Angle (x)




Period (y) vs. Amplitude (x)






Acceleration (y) vs..sin(x)

By studying data taken at large amplitudes, we notice a distortion in the plots $v_{ang}(t)$ and $a_{ang}(t)$ with respect to damped sinusoidal functions. Also the plot $a_{ang}$ ($\phi$) is no more linear in $\phi$. We may build the plot $a_{ang}$ ($\sin\phi$) : this will turn our linear, in agreement with the model $a_{ang}=-g/L\sin\phi$.
The period may be measured as a function of amplitude proving that at large amplitude the motion is not isochronous.

### 1.4 The "Atwood oscillator".

The necessary material for this experiment is: motion detector (Sonar), a bucket full of water, pulley with holder, two cylindrical masses with slightly different weights ($\Delta mg \approx$half of the weight of the water displaced by the heavier mass) with hook, strong and thin wire.
The pulley is attached to the table border and the two masses are suspend by the wire. The heavier cylinder is immersed into the bucket (it must be in equilibrium half immersed). The sonar is placed on ground and aimed at the cylinder which is out of the bucket. The sensors are zeroed and the oscillation and data acquisition are started.


The plot x(t), position vs. time, looks like the corresponding ones of mass-spring oscillator, and this might suggest it is harmonic motion.
The plots v(t) and a(t) instead show clearly (in the large amplitude region) that this motion is uniformly accelerated.
By repeating the analysis in the small oscillation region (when the cylinder does not exit completely from water) we observe that it is indeed a dumped harmonic motion.
One may recall the Archimedes' law to get a theoretical prediction for the restoring force that assumes a constant value in the first case $F= -\Delta mg \; \mathrm{sgn}(x)$ and varies linearly with displacement in the second one $F(x)=- \Delta mgx/L$ (where L is the cylinder length).
By measuring the period of oscillation T, and by fitting the T vs.$\sqrt{A}$ plot, one may test the validity of the model and study the role played by the total inertial mass of the system (that includes the cylinder out of the bucket, and eventually the pulley, if not negligible).
A further analysis may be performed also on dissipative effects, by comparing different slopes of the plot v(t) in the regions with the cylinder fully inside or fully outside water [see: B. Pecori, G. Torzo: "Come valorizzare un antico esperimento con la tecnica MBL: la macchina di Atwood…" *La Fisica nella Scuola*, **XXXI**, 83-96 (1998), and B. Pecori, G. Torzo, A. Sconza: "Harmonic and Anharmonic Oscillations investigated by using a Microcomputer Based Atwood's Machine", *Am. J. Phys*, **67**, 228-235 (1999)]

## 2. Thermodynamic transformations: evolution in time and state equations

Experimental investigations of thermodynamic transformations at introductory level have always been very limited because of the difficulties in performing simple, but conceptually relevant, lab experiments.

Low-cost and friendly on line data acquisition systems have opened very interesting possibilities in the experimental study of thermodynamics.

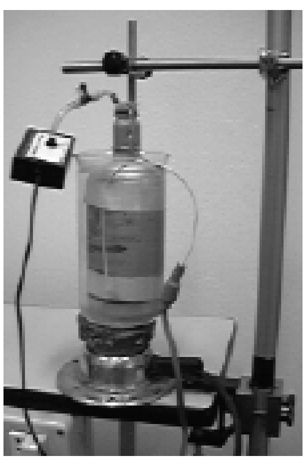
The possibility to easily collect measurements of thermodynamic variables versus time, at high acquisition frequency with virtually no limits in the number of samples, provides a detailed description of what goes on during the investigated transformation. This may have important implications on learning since students appear to need to reconstruct a description of the phenomenon in terms of relevant variables *versus time*, more similar to their spontaneous description, before they can accept and master the *time independent description* of the same phenomenon given by physics, in terms of equilibrium states.

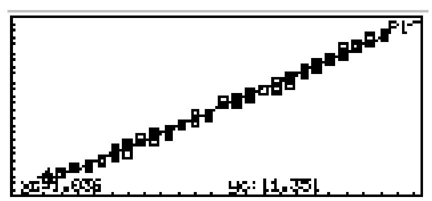
In this contribution we shall describe three experiments performed with a portable MBL (made of TI89, CBL, and sensors). The first two are related to *isochore* and *isotherm* transformations, the third one is a new version of a classic experiment to calculate the ratio of specific heats of air, by measuring a series of *adiabatic* transformations..

## 2.1. The gas thermometer

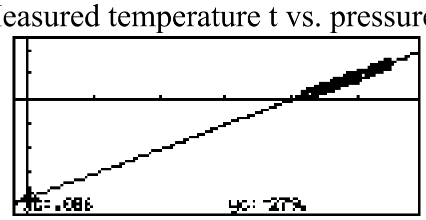
The dependence $p_t=p_0(1+\alpha t)$ offers a linear relation between pressure of a constant volume of gas and the temperature: this allows to use pressure as thermometric variable.

This relation may be re-written as $t=(p_t-p_0)/\alpha$, and therefore, once known the reference pressure $p_0$ and the coefficient $\alpha$, we get the temperature $t$ from measurements of $p_t$ using a known volume of air (contained in an aluminium beer bottle connected to a pressure sensor). Heating may be achieved in a water bath and the calibration of the gas thermometer requires comparison with data taken by a temperature sensor attached to the bottle.





Measured temperature t vs. pressure P



Linear extrapolation of t(P) to P=0

The linear relation shown in figure corresponds to : $t$ (Celsius)= B+A$p_t$ . The regression coefficients are B=–283 °C and A=282 °C/Atm.

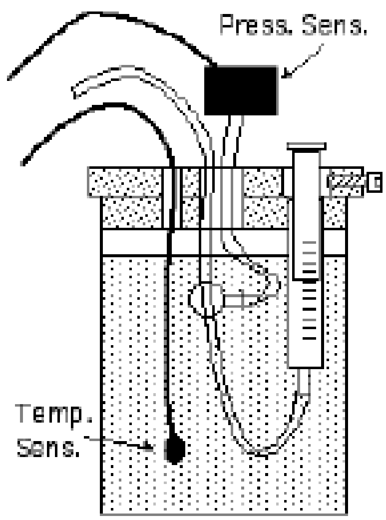
The intercept B may be interpreted as the temperature $t_a$ (in Celsius) at which the pressure of the (perfect) gas goes to zero. Because extrapolating the linear behaviour below that temperature would correspond to negative values of pressure, we can conclude that temperatures below $t_a$ cannot be achieved, and define $t_a$ as "absolute zero ".

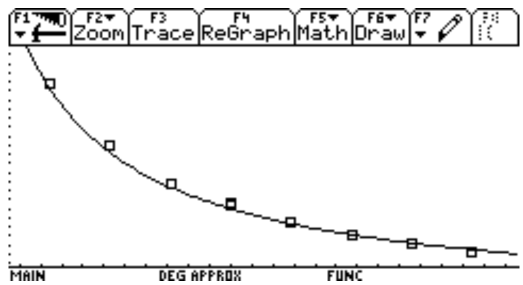
The temperature scale with $t_a$ as origin is named Kelvin scale and the “absolute” temperature is measured in Kelvin degrees $T$(K) $=t-t_a$.

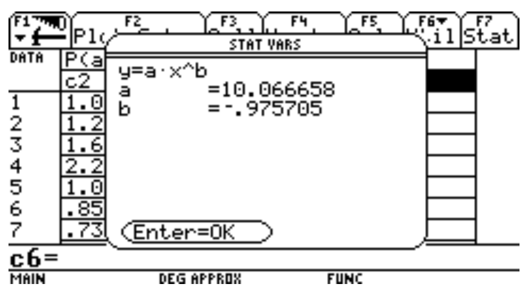
The slope (A=282 °C/Atm) may be compared to the value predicted by the state equation: $T/P=V/nR=V_M/R$, where $V_M/n=22.413\times10^{-3}$ $m^3$ is the molar volume. In the System International the predicted slope is A≈22.4×10–3/8.3≈2.7×10–3 K/Pa ≈273 °C/atm.

## 2.2 The ideal gas law: pV= nRT

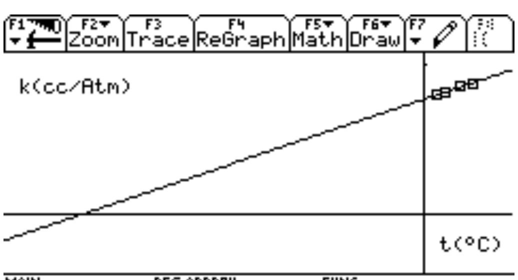
In this experiment the gas is again air, enclosed in a syringe connected to a pressure sensor and immersed in a water bath (thermostat) in a Pyrex vessel.
Moving the syringe piston we change the volume, whose value is read on the graduate scale, while pressure is measured by the probe. The bath temperature is measured by a temperature probe: both probes are connected through CBL to a graphic calculator.
The Pyrex vessel is firstly filled by a mixture of water and ice, to work at low temperature, but it may be placed onto the plate of an electric heater to achieve higher working temperature. We usually carry out 3-4 measurements, between 5°C and 40°C, in half an hour.
In TRIGGER/PROMPT mode at each measured pressure a volume value, read on the scale is typed in through the calculator keyboard.

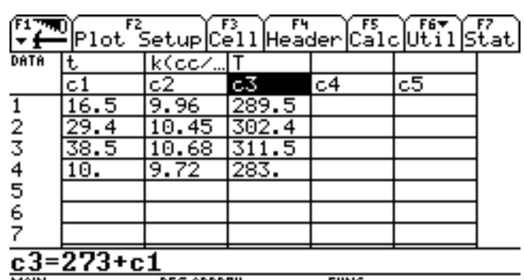



By repeating the experiment after thermalising the syringe in at various temperature, we obtain similar plots where for each temperature the product PV is constant.
By plotting all together the data of reciprocal pressures (1/P) versus volume we note that the slope k changes with temperature.




In a linear interpolation of $k$ as a function of temperature the data are well fitted by a straight line crossing the temperature axis ($t$, in Celsius) about at –273 Celsius.

By using a temperature scale shifted of this amount ($T$, in Kelvin) the variable $k$ will be exactly proportional to $T$.
Therefore the air, close to room temperature at pressures of the order of few Atmospheres, obeys the ideal gas law: $PV=nRT$, where $R$ is the universal gas constant $R$ = 8.314 (J mole$^{-1}$ K$^{-1}$) = 82.07 (Atm cm$^3$ mole$^{-1}$ K$^{-1}$) and $n$ is the number of moles.
The ideal gas law may be written in the form $V=(nRT)(1/P)$ which says that $k$ in the $V$ versus $1/P$ plots is $nRT$, proportional to the absolute temperature.

## 2.3 The Rüchardt's experiment

The reversible adiabatic transformations in a perfect gas obey to the Poisson equation $PV^{\gamma}$=cost, where coefficient $\gamma$ is the ratio $c_p/c_V$ between the constant pressure and the constant volume specific heats.
Obviously in a reversible adiabatic transformation the temperature does changes, and its values may be calculated using the state equation, e.g. by substituting $P=nRT/V$ into the Poisson equation: $T\,V^{\gamma-1}$= cost. The method invented by Rüchardt (1929) to measure $\gamma$ involved a series of reversible adiabatic compressions/expansions produced by a sliding piston oscillating inside a vertical cylindrical neck attached to a bottle of volume $V$
Assuming no friction and no leaks between the piston and the neck, the system may be modelled as follows. The gas interacts with the outside only through the piston, that performs work on it.
If the piston mass is $m$ and the initial pressure $P_0$, the equilibrium condition is reached in the gravitational field for the pressure $P$:

$$P = P_0 + mg/A\ ,$$

where $A$ is the neck cross-section and $g$ is the gravity acceleration.
By displacing the piston of a quantity $x$ from equilibrium, the volume change is

$$dV = xA.\ ,$$

and the corresponding force $F$ acting onto the piston

$$F = A\, dP$$

Because pressure and volume are related by

$$dP = -(\gamma P/V)\, dV\ ,$$

the resulting force $F$ onto the piston may be written:

$$F = A\, dP = -A(\gamma P/V)dV = -A^2\,(\gamma P/V)x,$$

This shows that the force is quasi-elastic ($F=-kx$, with a "spring constant" $k=\gamma A^2\,P/V$).
Free piston oscillations in the neck must therefore be nearly harmonic, obeying to the differential equation:

$$a = \frac{F}{m} = \frac{d^2x}{dt^2} = -\frac{\gamma PA^2}{mV}x = -\omega^2 x$$

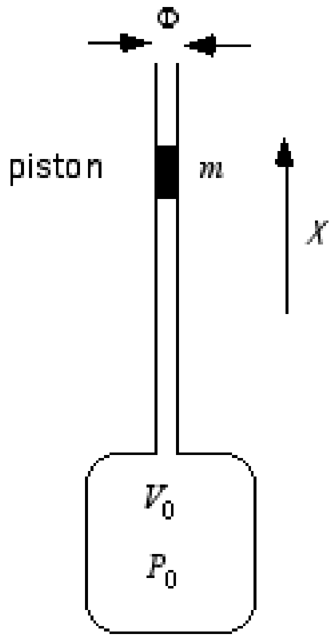
where the angular frequency $\omega$ is

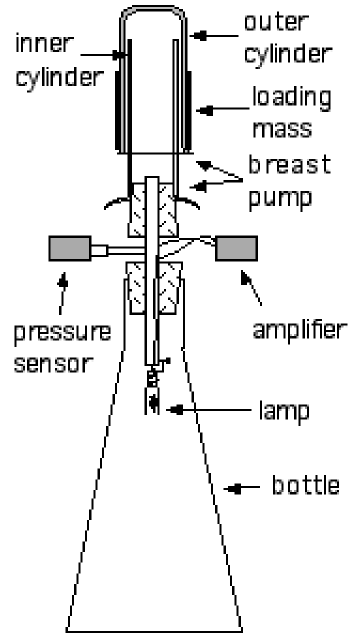
$$\omega = 2\pi/\tau = \sqrt{\frac{\gamma\, PA^2}{mV}}$$

(here $\tau$ is the period) and the coefficient $\gamma$ may be calculated from the four measurable quantities $m$, $A$,$V_O$, $P_O$, $\tau$:

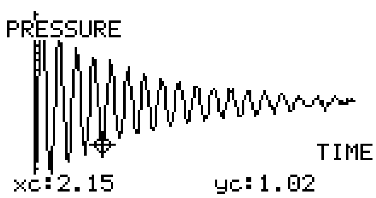
$$\gamma = \frac{4\pi^2}{A^2P\tau^2} = \frac{mV}{A^2P\omega^2}$$

Using CBL and graphic calculator we built an apparatus to record the time evolution not only of the piston position (i.e. of the volume) with a sonar, but also of the pressure with a Vernier pressure probe and of the temperature, with an home made temperature probe.

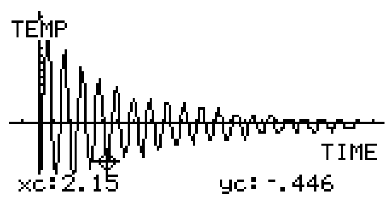


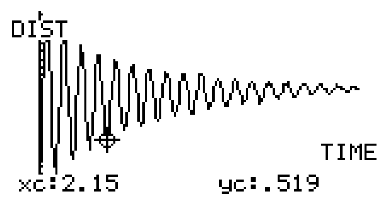

The device is shown in the figure: we replaced the tube and piston with a breast-pump (commercially available, that avoids the need of the costly and fragile glass tube perfectly calibrated to the piston). The piston diameter is therefore the inner one of the oscillating outer cylinder of the breast-pump, and its mass may be easily changed by loading it with a metal collar. The thermometer is obtained from the filament of a lamp (whose glass bulb was perforated) and by measuring the filament resistance (tungsten resistance thermometer).
The plots that can be obtained, and from which one may easily derive the oscillation period, are shown hereafter.




Pressure

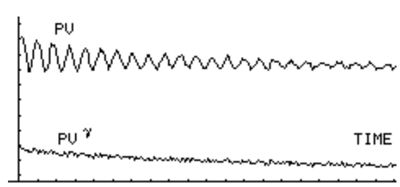



Temperature




Volume

With the recorded values one may also check the validity of Poisson equation, building the graphs $PV^\gamma$ versus time or versus temperature, and by comparing them with the corresponding graph of the product PV.

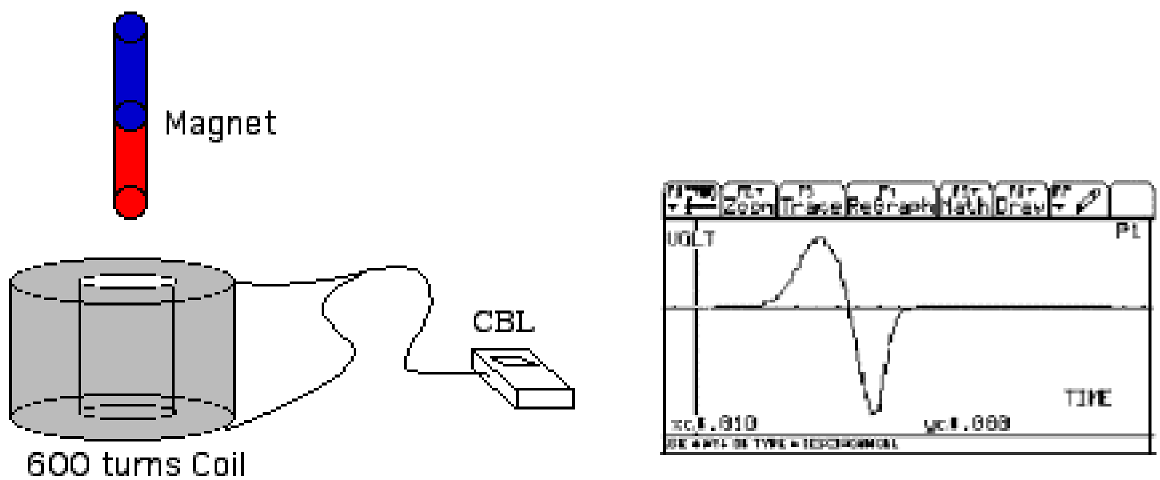



Test of the Poisson equation

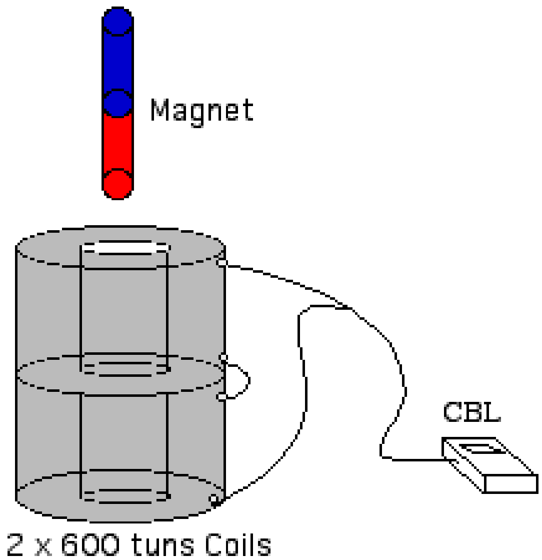
[see also: G. Torzo, G. Delfitto, B. Pecori, P. Scatturin: "A new MBL version of the Rüchardt's experiment for measuring the ratio $\gamma = C_p/C_v$ in air.” *Am. J. Phys.* **69**, (11), 1205-1211 (2001)]

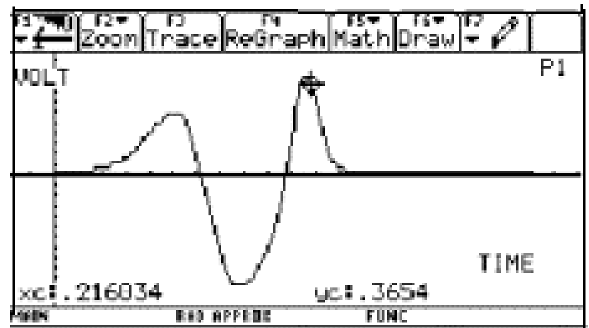
### 3.1 Magnet falling through a coil

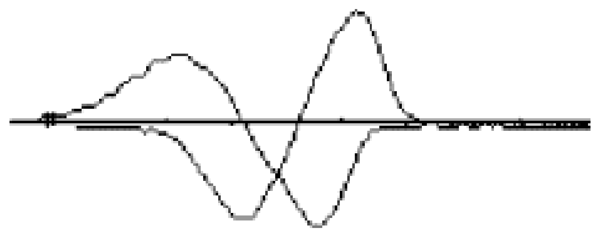
The transients related to magnetic induction are usually fast phenomena. An MBL system, by using a trigger threshold to start acquisition, let us monitor a large variety of such phenomena and test their consistency with theoretical predictions. In the following examples we used a Vernier magnetic field sensor and a voltage probe connected to CBL.
When a bar magnet falls through a coil, thus changing the magnetic flux linked to the coil, the induced voltage lasts usually few tenth of a second.




The graph of the induced voltage ε(t) versus time shows two peaks, one positive and one negative, that are particularly asymmetric when the magnet starts falling close to the coil. The bar speed, that steadily increases with time, is small when the magnet enters the coil and therefore the peak is smaller and lasts longer with respect to the peak corresponding to the magnet exiting the coil.
The calculator makes easy to calculate the integral of the curve, giving an immediate and convincing experimental proof of the Faraday-Neumann Law, that predicts a voltage proportional to the time derivative of the linked magnetic flux: $\varepsilon(t) = -\Delta\Phi/\Delta t$
The integral ofε(t), i.e. the area enclosed between the curve and the time axis, equals the total magnetic flux change, and it must be zero if the initial and final fluxes are negligible. In other words, the two areas corresponding to the positive and negative peaks must turn out of equal modulus and opposite sign: this is exactly what we find (in the reported example: 0,017 V s and -0,016V s).



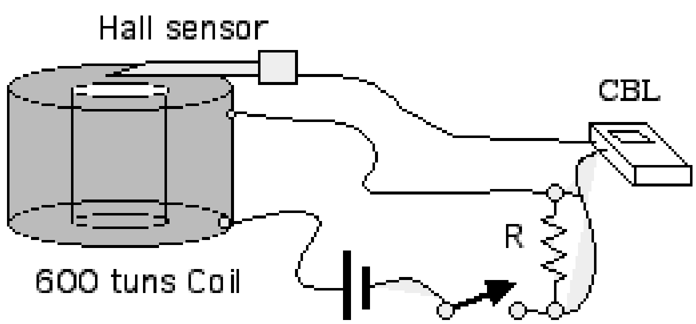



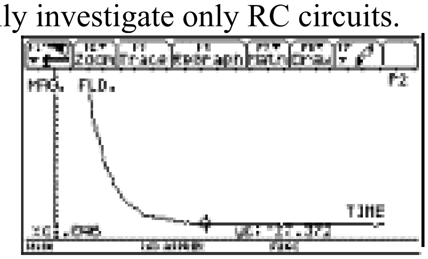
An effect quite interesting is obtained superimposing two equal coils connected in series but with opposite windings. The resulting plot appears surprising, at first sight. But considering it as a superimposition of the two individual plots due to the single coils it appears reasonable.

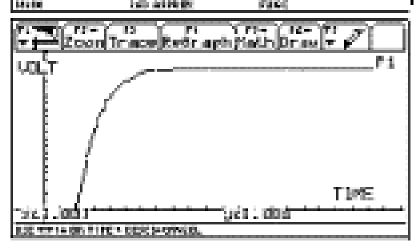
### 3.2 The time constant in R L circuits

MBL make possible the study of transients in RL circuits without using square-wave signal generator and oscilloscope, instruments that are not always available in Italian first level secondary schools laboratories, and that are not considered user friendly.

Changes of current and voltage that occur when switching on and off a circuit with inductances and resistances reach stationary values through an exponential transient as RC circuits, but the time constant $\tau$, in this case is L/R and we cannot increase L without increasing at the same time also R. With the coils that are commonly available in a school laboratory the time constant is usually too small to be measured without automatic trigger. This is why we usually investigate only RC circuits.



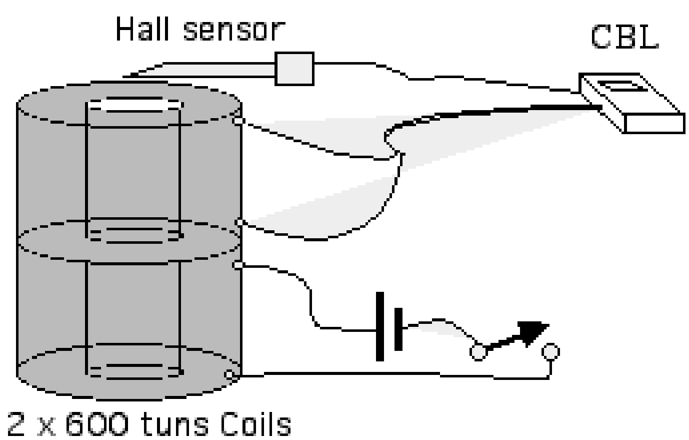



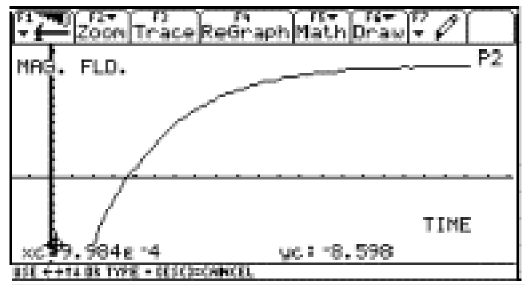

A coil with laminated-iron core is connected to a d.c. power supply through a switch and a small resistor (R=10 ohm) and we record the time evolution of the current and of the magnetic field at the coil centre when closing the loop. The current is measured by the voltage probe at the resistor ends, and the magnetic field by the sensor placed onto the iron core.

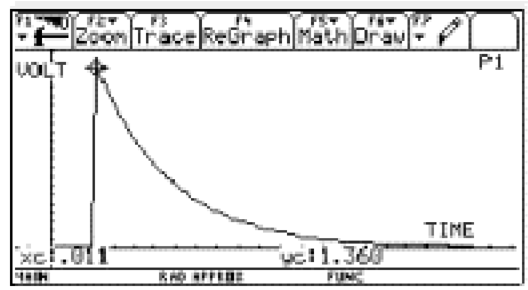
Magnetic field and current approach both exponentially the limit value. By interpolating the recorded data, we may calculate the time constant and compare it with the value of the ratio L/R, when these are known. The experiment may be repeated with different type of core, while keeping constant other parameters, to compare the different resulting plots.

### 3.2 Mutual induction

With a second coil placed onto the first one and linked to the same core, we may study the changes of magnetic field and the voltage induced into the second coil.



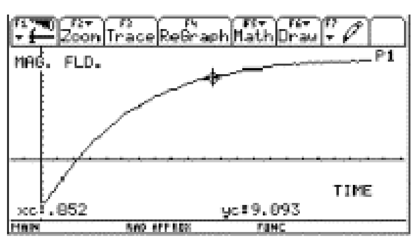




The voltage induce in the second coil ("secondary winding") behave as the time derivative of the magnetic field, as predicted by the theory.

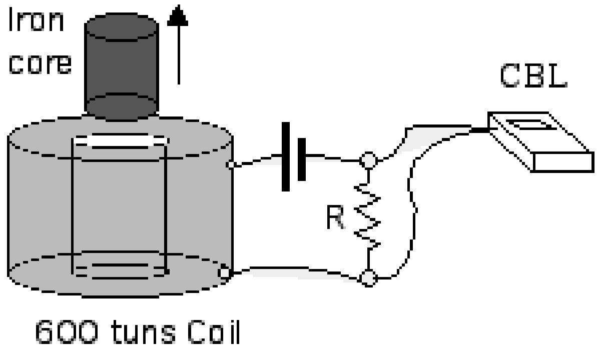
### 3.3 Parasitic currents and Lenz Law

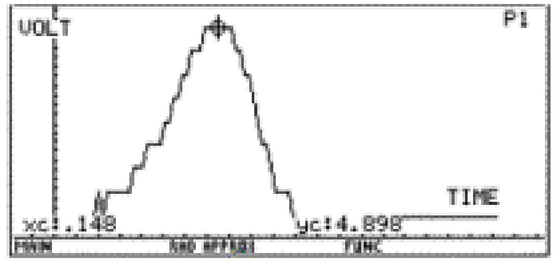
The double coil system above described is an example of transformer. We may use it again to study the behaviour of the magnetic field in the coil core when the secondary winding is shorted. We substitute the voltage probe with a short conducting wire, and we switch on the current in the primary winding. The magnetic field probe records a signal similar to the previous one, but longer lasting.




The reason is due to the parasitic currents, induced in the shorted secondary winding, and flowing in opposite direction with respect to the current flowing in the primary winding, as predicted by Lenz Law.

Another phenomenon closely related to the Lenz Law may be observed when we quickly extract the core from the coil inserted in the R L circuit.

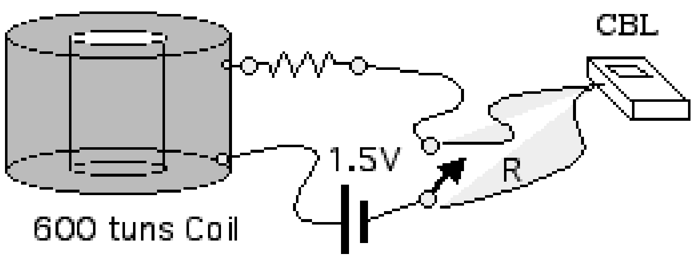


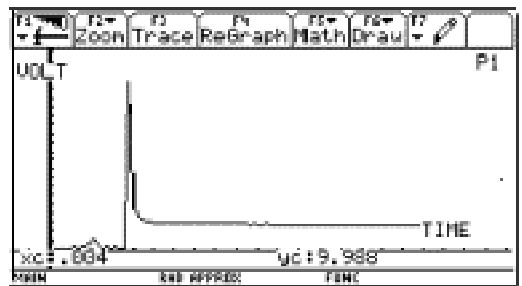



The voltage probe records, in the signal across the resistance, a peak due to a current surge. In fact during the core extraction the magnetic flux decreases, due to the lower magnetic permeability of air with respect to that of the iron core, and the current increases to oppose this flux change.

### 3.4 Voltage surges at switch-off

The current flowing in a circuit cannot be zeroed suddenly: when it is switched off extra-currents are generated (trying to keep constant the linked magnetic flux) an the corresponding overvoltages may even reach dangerous values, if the inductance is large.






If we connect the voltage probe across the switch, when this is opened, the voltage goes from the initial 0 to the final power supply value (1,5 V in our battery) crossing values much larger. In parallel with the switch we have the probe impedance (Z=750 kΩ), and when the switch opens the current I that was flowing through it is forced to pass through Z, so that the $V=ZI$. The current decays with a time constant $\tau = L/Z$, and this explains the peak.