Understanding the physics of bungee jumping

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Abstract
Changing mass phenomena like the motion of a falling chain, the behaviour of a falling elastic bar or spring, and the motion of a bungee jumper surprise many a physicist. In this article we discuss the first phase of bungee jumping, when the bungee jumper falls, but the bungee rope is still slack. In instructional material this phase is often considered a free fall, but when the mass of the bungee rope is taken into account, the bungee jumper reaches acceleration greater than g. This result is contrary to the usual experience with free falling objects and therefore hard to believe for many a person, even an experienced physicist. It is often a starting point for heated discussions about the quality of the experiments and the physics knowledge of the experimentalist, or it may even prompt complaints about the quality of current physics education. But experiments do reveal the truth and students can do them supported by information and communication technology (ICT) tools. We report on a research project done by secondary school students and use their work to discuss how measurements with sensors, video analysis of self-recorded high-speed video clips and computer modelling allow study of the physics of bungee jumping.

M This article features online multimedia enhancements

The thrilling physics of bungee jumping

Leaping from a tall structure such as a crane or a bridge to which the jumper is attached by his or her ankles by a large rubber band is a thrilling experience. This event, better known as bungee jumping, can also serve as an intriguing context for physics lessons and practical work [1, 2]. Physics can help to give answers to safety questions like 'How do I know that the rubber band has the right length and strength for my jump?' and 'How am I sure that the g-forces are kept low enough that bungee jumping does not hurt?'

A simple energy model of a bungee jump can be used to generate strain guidelines and practical design equations for the sizing of an all-rubber bungee rope [3]. In many studies (e.g., [1, 4–6]), the motion is considered one dimensional, the rope is modelled as a massless elastic, the jumper is replaced by a point mass, aerodynamic effects are ignored, and the stress–strain curve of the rope is assumed linear (i.e., Hooke's law applies). The bungee jump can then be divided into three phases: (i) a free fall (with acceleration of gravity g) of the jumper when the rope is still slack; (ii) the stretch phase until the rope reaches its maximum length;

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and (iii) the rebound phase, consisting of a damped oscillatory motion.

Several assumptions in this model of bungee jumping can be removed so that the results of models and experiments are in better agreement. Kockelman and Hubbard [7] included the effects of the elastic properties of the rope, jumper air drag, and jumper push-off. Strnad [8] described a theoretical model of a bungee jump that takes only the mass of the bungee rope into account. The first phase of bungee jumping can also be related to other phenomena such as the dynamics of a falling, perfectly flexible chain suspended at one end and released with the two ends near to each other at the same vertical elevation [9–14]. Experiments, numerical simulations, and analytical models discussed in the literature (also for discrete models of chains) point to the paradoxical phenomenon that the tip of a freely falling, tightly folded chain with one end suspended from a rigid support moves faster than a free falling body under gravity. This phenomenon is the main subject of this article, but we place it in the context of a research project of secondary school students and discuss how technology can contribute to the realization of such challenging practical investigations.

A secondary school student project

In the Dutch examination programme of senior secondary education, which is organized in so-called profiles consisting of fixed subject combinations, students are required to build up an examination portfolio by carrying out some small practical investigation tasks and one rather large (80 h), cross-disciplinary research or design assignment. In the 'Nature and Health' and 'Nature and Technology' profiles, teams of two students may collaborate in creating their piece of work as independent experimental research on a topic of their own choice.

In 2003, Niek Dubbelaar and Remco Brantjes, who were two secondary school students from the Bonhoeffer college in Amsterdam, teamed up to investigate the physics of bungee jumping, triggered by their own interest and an article [4] on www.bungee.com. In particular, they were intrigued by the alleged 'greater than g acceleration' of a bungee jumper and, during their experimental work, they contacted one of the authors of a published paper on this subject [14] for more information.

The students formulated the following research question: 'How large is the acceleration in a bungee jump and to what degree is this acceleration influenced by the relative mass of the rope and the jumper?' Using the analogy of the motion of a bullwhip, they hypothesized that the acceleration would be greater than g and that this effect would be more dramatic if the rope was relatively heavy as compared with the jumper. They collected position–time data through video measurements on a dropped scale model (an Action Man toy figure) and on dropped wooden blocks of various weights attached to ropes of various stiffnesses. Figure 1 is a sketch of the experimental setting, taken from the students' report.

The velocity and acceleration of the dropped object were computed by numerical differentiation. Soon the students realized that the mass ratio between rope and objects was too low to see a clear result and they repeated the experiment with objects of larger mass ratio. The graph of the acceleration at the moment that the block has fallen a distance equal to the rest length of the elastic as a function of the mass ratio of the elastic and the block is shown in figure 2, together with the graph of the following theoretical result:

$$a = g\left(1 + \frac{\mu\,(4+\mu)}{8}\right), \qquad (1)$$

where μ is the mass ratio of the elastic and the wooden block. This formula can be found in [14] and on the Internet [15]. The students noted that the graphs obtained by measurement and theory are alike, with the theoretical values just a bit higher. They attributed the difference mainly to the development of heat during the motion.

Not knowing that a Dutch physics teacher had published around the same time on an experimental verification of the physics of bungee jumping [16], the students wrote an article about their work that was published in the journal of the Dutch Physics Society [17]. It triggered quite a number of reactions in the journal and for almost a year on the Internet. It seemed that a major part of the physics community, at all levels of education, were suddenly playing with ropes, chains, elastics, and so on. There were complaints about the quality of physics teaching in the Netherlands, arguing that obviously(!) $a \leqslant g$ and that the students' work proved that the level of physics education

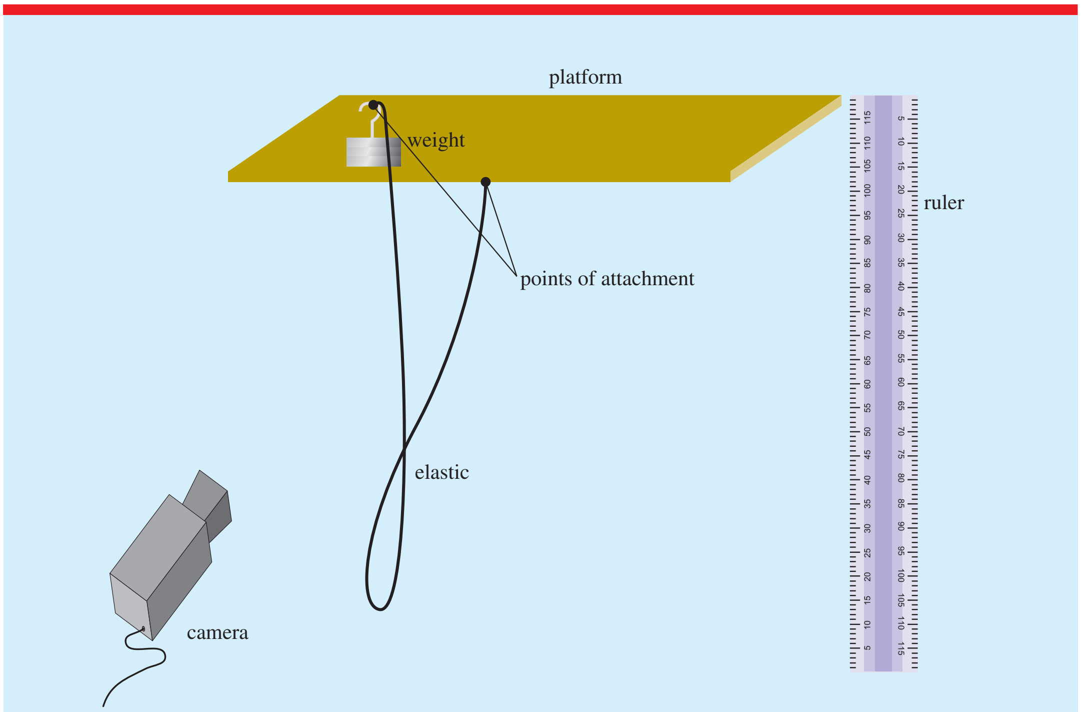

Figure 1. Sketch of the experimental setting.

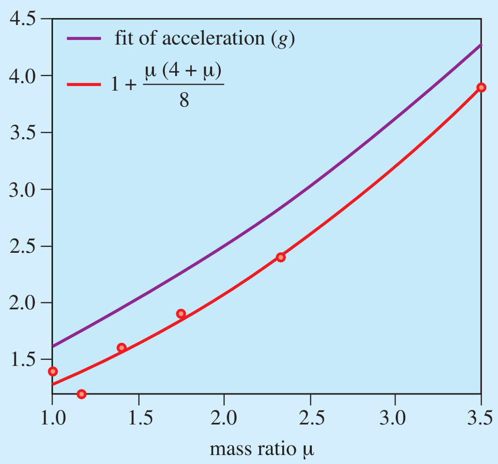

Figure 2. Graphical display of experimental results and fit (purple) and computed values (red).

in the Netherlands had degraded in the last few decades.

The editorial commentary was subtle, but to the point: 'The students who wrote the paper may consider it a compliment that scepticism overcame professional physicists and physics teachers. That's how (or maybe it is just the point that) experienced intuition can be wrong.'

In the same issue, two theoretical physicists [18] agreed with the findings of the students and they explained that physics intuition is easily fooled, as everyone is taught the Galilean paradigm of the motion of constant masses, according to which every acceleration must be produced by a force. A launched rocket and a falling chain or slinky are important counterexamples to this line of thought. Actually, as we will see in the theoretical section, believing the statement $a > g$ means giving up or generalizing the law $F = ma$.

Other experiments on bungee jumping

An in-service training module on bungee jumping has been developed in the framework of the European project 'Information Technology for Understanding Science' (IT for US). All teaching and learning activities, which can be downloaded from the project's website [19], are based on the use of the COACH environment[3] [20] for data

[3] COACH 6 is a versatile computer learning and authoring environment that provides integrated tools for MBL-based measurement, control activities, digital image and video analysis, and computer modelling. It has been translated into many languages, is used in many countries, and the CMA Foundation distributes it. For more information, see www.cma.science.uva.nl.

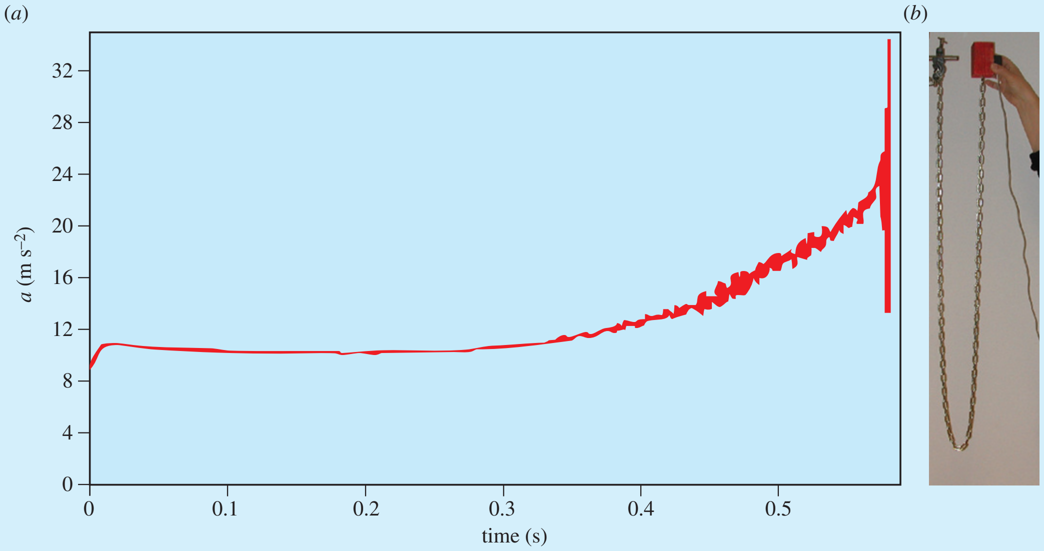

Figure 3. Acceleration of the chained block (*a*) and the experimental setting (*b*).

logging, for video analysis, and for computer modelling, simulation and animation. One of the laboratory experiments is the measurement of the force during stretching of the elastic with different masses and of the force encountered by jumpers on different bungee ropes. Another bungee jumping related experiment is the measurement of the acceleration of a dropped, chained wooden block using an attached accelerometer. Figure 3 shows a measurement result (a) and the experimental setting (b). Without doubt, the acceleration is greater than g and reaches its maximum value when the chain is completely stretched.

Originally, the students made video recordings of chained objects falling from a height of about 4 m with a webcam operating at a speed of 30 frames s^{-1}. This corresponds to a data set of 15 measured positions. The size of this data set is too small for computing reliable accelerations through numerical differentiation. Much better results could be obtained with a high-speed camera. However, at the time that the students did their project such cameras were very expensive. Nowadays point-and-shoot cameras that can record videos at a speed up to 1000 frames s^{-1} are available at a consumer level price.

We tried this out in the following experiment (see figure 4): two identical wooden blocks are dropped at the same time from a height of a couple of metres. One block is in free fall and the other block is chained. The chained block touches the ground earlier than the block that is in free fall, which can be observed with the naked eye and can be recorded with a common camcorder. This implies that the chained block must have acceleration greater than the acceleration of free fall. The motion of the blocks is recorded with a high-speed camera at a speed of 300 frames s^{-1} (a video clip is available in the online version of the journal at stacks.iop.org/physed/45/63/mmedia). In the video analysis tool of COACH [20], the vertical position of the blocks can be automatically measured via point tracking. Manual data collection would be too time consuming.

Figure 5 shows the graphs of the measured distances of the blocks, relative to the points where they were released (i.e., we select a coordinate system with a positive vertical coordinate in the downward direction), and the velocity–time graphs of the blocks. These graphs have been obtained with a numerical differentiation algorithm that is based on a penalized quintic spline smoothing technique (for details about the point tracking and numerical differentiation algorithms in COACH, we refer the reader to [21]). The blue velocity–time graph, which is almost a straight line, belongs to the free falling block. The red graphs, where the cross-hairs in scan mode meet, belong to the chained block that has already

Figure 4. Dropping two wooden blocks simultaneously from a height of a few metres, while one of the blocks is chained and the other is in free fall.

travelled at the selected moment a greater distance than the free falling object.

Theoretical underpinning of $a > g$

Kagan and Kott [14] derived equation (1) by applying the law of conservation of energy. This is correct but it does not give much insight into what is really going on. In a more direct approach, Pasveer and de Muynck [15] applied the following equation of motion:

$$\sum F = \frac{\mathrm{d}p}{\mathrm{d}t}, \tag{2}$$

where the left-hand side is the sum of forces F acting on the object and the right-hand side is the derivative of the momentum p of the moving object. However, they did not reproduce the result of Kagan and Kott. We resolve this in the next section.

In the case of the chained block we do not deal with a falling rigid body, but instead with an object of changing mass, not unlike the moving end of a lion tamer's whip. Therefore, the traditional form of Newton's second law $F = ma$ is not suitable here and should be replaced by the following generalized form:

$$\sum F = \frac{\mathrm{d}p_{\mathrm{obj}}}{\mathrm{d}t} = \frac{\mathrm{d}m_{\mathrm{obj}}}{\mathrm{d}t}v_{\mathrm{obj}} + m_{\mathrm{obj}}a_{\mathrm{obj}}, \tag{3}$$

where m_{obj}, v_{obj}, a_{obj}, and p_{obj} represent the mass of the object (changing in time), and the velocity, acceleration and momentum of the object, respectively, and F represents a force acting on the object.

The most interesting object is in this case the wooden block together with its attached chain. The picture of the experimental setting shown in figure 3(b) illustrates that the moving part on the right-hand side diminishes during the fall because

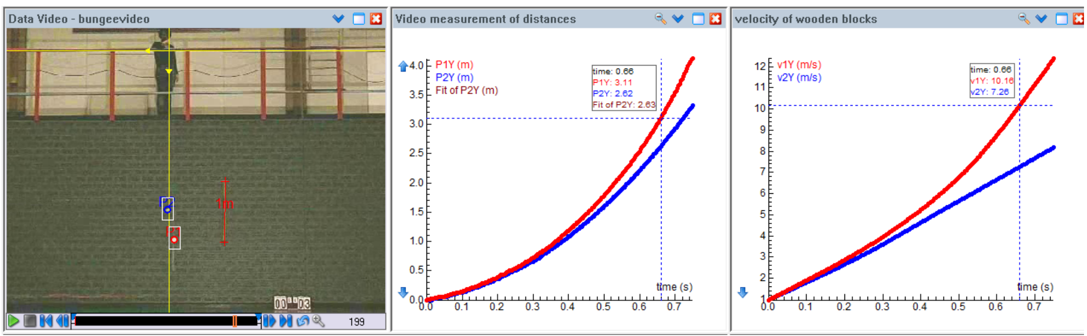

Figure 5. Video analysis of two dropped blocks. The red position and velocity–time graphs relate to the chained block and the blue curves belong to the free falling block.

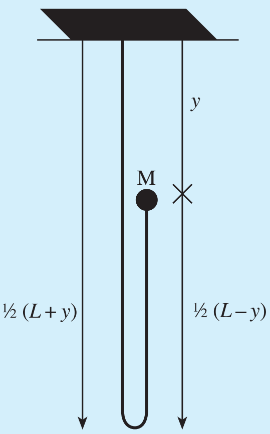

Figure 6. Sketch of the block of mass M attached to a chain of length L that has already fallen a distance y and is travelling at a speed v with acceleration a.

part of the chain 'moves' to the left-hand side. This implies

$$\frac{\mathrm{d}m_{\mathrm{obj}}}{\mathrm{d}t} < 0. \tag{4}$$

Because $\sum F = m_{\mathrm{obj}} g$ when only gravitational force is taken into account and $v > 0$ in the direction of motion, $a > g$ must hold!

A detailed mathematical model

With the goals in mind of being able to compare theoretical results with experimental results and being able to understand the graphical computer model shown in the next section, we give a detailed derivation of the equation of motion. Figure 6 is a sketch of the situation of a falling chained block. The following symbols are used (numerical values applicable in the experiment and the computer model are in brackets):

M = mass of the block (0.125 kg);
m = mass of the chain (0.68 kg);
$\mu = m/M$ = the chain : block mass ratio;
L = length of the chain (4.15 m);
g = acceleration due to gravity (9.81 m s^{-2});
a = acceleration of the chained block;
v = speed of the chained block;
y = distance travelled by the block.

The object under consideration is the right-hand side consisting of the chained block and the moving part of the chain. We call this the free side of the bend. Thus

$$\begin{aligned} m_{\mathrm{obj}} &= M + \frac{1}{2}(L-y)\frac{m}{L}, \\ \frac{\mathrm{d}m_{\mathrm{obj}}}{\mathrm{d}t} &= -\frac{mv}{2L}. \end{aligned} \tag{5}$$

The left-hand side of equation (3) is not as simple as it may seem at first sight. Of course a gravitational force acts on the chain on the free side of the bend and friction forces, but as Calkin and March [9] pointed out, there is also a nonzero tension on this part, which additionally pulls the chain down.

We consider in this article an alternative perspective, similar to the viewpoint of Biezeveld [16]: the free side of the bend falls with speed v, the fixed side of the bend hangs still, and the bend, where links of the chain in motion come to rest, moves at speed $u = \frac{1}{2}v$. In equation (3), v_{obj} denotes the velocity with which the mass leaves the moving system. In our case, this velocity therefore almost instantaneously decreases from v to 0 and is taken to be the average value, i.e., the speed of the bend. We ignore friction forces and only take the gravitational force into account:

$$\sum F = m_{\mathrm{obj}} g, \quad v_{\mathrm{obj}} = u = \tfrac{1}{2}v, \quad a_{\mathrm{obj}} = a. \tag{6}$$

It is noted that Pasveer and de Muynck [18] erroneously used $v_{\mathrm{obj}} = v$. Substitution of equations (5) and (6) into equation (3) gives

$$a = g + \frac{\frac{1}{2}\mu v^2}{\mu(L-y) + 2L}. \tag{7}$$

Instead of considering the velocity v as a function of time we can also consider it as a function of the vertical position y:

$$a = \frac{\mathrm{d}v}{\mathrm{d}t} = \frac{\mathrm{d}v}{\mathrm{d}y}\frac{\mathrm{d}y}{\mathrm{d}t} = v\frac{\mathrm{d}v}{\mathrm{d}y} = \frac{1}{2}\frac{\mathrm{d}v^2}{\mathrm{d}y}. \tag{8}$$

Combining equations (7) and (8) we get the following linear, first-order ODE:

$$\frac{\mathrm{d}v^2}{\mathrm{d}y} + \frac{\mu v^2}{\mu(y-L) - 2L} = 2g. \tag{9}$$

A person who has already a fair amount of knowledge of calculus can easily solve the initial value problem with $v^2(0) = 0$. Others may need a computer algebra system. The solution of the differential equation is

$$v^2 = gy\frac{4L + \mu(2L - y)}{2L + \mu(L - y)}. \qquad (10)$$

Substitution of equation (10) into equation (7) gives

$$a = g\left(1 + \frac{\mu y(4L + \mu(2L - y))}{2(\mu(L - y) + 2L)^2}\right). \qquad (11)$$

Taking $y = L$ in equation (11) gives equation (1).

An analytical formula for the time T needed for the chained block to reach its lowest point can be found with a computer algebra system like MAPLE. As Strnad [8] showed, this formula needs the notion of elliptic functions and is beyond secondary school level. However, two interesting limiting cases for the falling time T are the free fall of an object over a distance L ($\mu \downarrow 0$) and the falling chain fixed on one side and free on the other side ($\mu \to \infty$):

$$\lim_{\mu \downarrow 0} T = \sqrt{\frac{2L}{g}}, \qquad \lim_{\mu \to \infty} T \approx 0.847\sqrt{\frac{2L}{g}}. \qquad (12)$$

This illustrates that when an object and a chain of length L that is fixed at height L on one side and is held up on the other side are released from height L at the same time, the chain reaches the ground earlier than the free falling object.

Computer modelling and simulation

Secondary school students are most probably not able to solve the differential equation (9) by hand. But even if they have the knowledge of calculus, it still does not give formulae for the vertical position, velocity, and acceleration as functions of time. To obtain these, the nonlinear, second-order, ordinary differential equation (7) in $y(t)$ must be solved for the initial values $a(0) = v(0) = 0$. It suffices to find a numerical solution and the modelling tool of COACH 6 brings this within reach of secondary school students.

Biezeveld [16] used the text-based version of the modelling tool, which is in fact programming in a computer language that is dedicated to mathematics, science and technology education. The authors take the view that the system dynamics-based graphical mode of modelling, which is similarly implemented in modelling tools such as STELLA and POWERSIM, is simpler for students and accessible at secondary school level (see also, for example, [22]). One of the arguments is that this graphical representation symbolizes both the system of equations and the numerical algorithm used to solve it, which seems to make it easier for students to build their own models and to achieve results of good quality. A user can express his or her thoughts about the behaviour of a dynamic system in the graphical representation, and these ideas are then automatically translated into more formal mathematical representations.

The upper left corner of the screen shot in figure 7 is an example of a graphical model. It computes the motion of a free falling block and a chained block according to the previously presented theory. For example, the second formula in equation (5) is behind the outflow dm_dt, and the formula $g + 0.5m'_{obj}v/m_{obj}$ is behind the inflow a.

The graphical model in fact represents a computer model, which provides in many cases an iterative numerical solution of a system of differential equations, e.g., via a Runge–Kutta algorithm for integrating the corresponding differential equation.

In figure 7 also shown are the position and velocity–time graphs of a simulation run and the graph of the ratio a/g, which increases while the chained block is falling. Parameter values have been chosen such that the model-based graphs for the chained block are in good agreement with the graphs obtained through measurements. Prediction and measurement match very well: the time that the chained block needs to reach its lowest position according to equation (12) for the given masses and chain length is equal to the measured time and to the time found in a simulation run within an error margin of 1%!

Animation

The computer model can also be used to create an animation of the motion of the chained and free falling block. The tool windows on the right-hand side of figure 7 are a slider and an animation window that displays the simulation results as

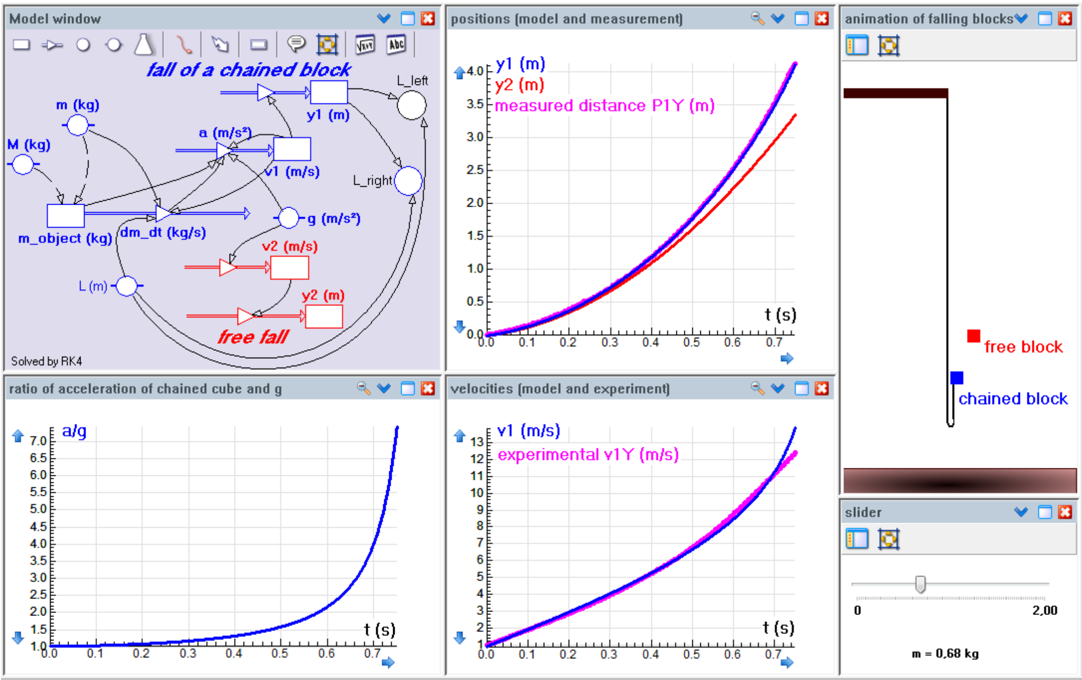

Figure 7. Screen shot of a COACH activity in which a graphical model implements the motion of a chained block (1) and a free falling block (2). The position and velocity–time graphs of a simulation run have been plotted. Parameter values are chosen such that the calculated plots for the chained block match well with the measured data shown as background point plots. The graphical model is connected with a slider and an animation window.

animations where model variables are presented as animated graphics objects. A student can interact with the model and the animation through a slider bar, that is, select the value of the mass of the chain before the start of the simulation and also during the model run. Animation allows students to concentrate on understanding a phenomenon with the help of simulations before going into the details of how the simulations have been implemented by means of computer models.

Conclusion

Admittedly, the mathematics and physics of the falling chained block is more complicated than usually is the case for problems in physics schoolbooks. The main reasons are that (i) motion of a non-rigid body is involved; and (ii) the factor $1/2$ for the velocity at which links of the chain come to rest at the bend, which is required in the extra term in the generalized Newton law, is easily overlooked (as in [18]). Selling points of the students' project are that it is much more challenging work than common practical work, and that it brings both physics teachers and students down to earth as regards the indiscriminate application of Newton's second law $F = ma$.

Furthermore, theory and experiment supplement each other in the activities. We take the view that modelling is not just the understanding of the (computer) model with the hope and expectation that nothing went wrong during the theoretical work; it includes sound understanding of the underlying physics principles and of the assumptions made in the modelling process, as well as validation of the model on the basis of experiments. The latter point is in our opinion essential in good physics education. The words of the Nobel Prize winner Martinus Veltman (cf. [23]): 'If one removes experiments, physics becomes religion. Then the facts do not count anymore, but the opinions of someone who was appointed pope' also hold for physics education.

The main role of technology in the students' investigative work is to allow them to collect real-time data of good quality, to construct and use computer models of dynamics systems, and to compare results from experiments, models, and theory with each other. For measuring, data processing and analysis, modelling, and animation, several tools are available for education. For example, Sismanoglu *et al* [24] used a camcorder to record the motion of a falling chain. Using the freely available video tool VIRTUALDUB (www.virtualdub.org) they went frame by frame through the recorded video clip and manually did measurements on each frame. The spreadsheet program EXCEL was used for making tables and graphs, and for computing velocity and acceleration using finite difference methods. In other words, these authors used a set of rather disconnected tools. In such an approach, in our opinion, one runs the risk that one ends up with a grab bag of tools that are not geared up to work with each other and all require considerable time to familiarize oneself with. The computer modelling and construction of an animation described in this article could also have been carried out in another computer modelling environment, for example MODELLUS [25]. The drawback for education could then be that it is onerous in this environment to compare modelling results with experimental results. In contrast, COACH [20, 26] has been designed with the vision of a hardware and software environment in which tools for measuring (sensor based and through video capturing), data processing and analysis, control experiments, modelling and animation are integrated in a single multimedia authoring package that supports students' learning in an enquiry-based approach to science education. A learn-once, use-often philosophy of educational tools is more easily realized in such an environment. Another advantage of a single environment compared to a software suite is the possibility of combining different tools in one activity.

In general, students have a positive attitude toward the use of technology in science education, especially when they recognize that this allows them to do activities similar to those in which 'real' scientists engage. The satisfaction of ICT-supported investigative work is highest when experiment, model and theory are in full agreement, as is the case in the presented study of achieving an understanding of the physics of bungee jumping.

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References

[1] Horton P 2004 Elastic experiment is licensed to thrill *Phys. Educ.* **39** 326–8
[2] Turner R and Taylor B 2005 Physics fairs in the classroom: bungee ropes and killer tomatoes *Phys. Educ.* **40** 515–6
[3] Kockelman J and Hubbard M 2004 Bungee jumping cord design using a simple model *Sports Eng.* **7** 89–96
[4] Menz P 1993 The physics of bungee jumping *Phys. Teach.* **31** 483–7
[5] Palffy-Muhoray P 1993 Problem and solution: acceleration during bungee-cord jumping *Am. J. Phys.* **61** 379
Palffy-Muhoray P 1993 Problem and solution: acceleration during bungee-cord jumping *Am. J. Phys.* **61** 381
[6] Martin T and Martin J 1994 The physics of bungee jumping *Phys. Educ.* **29** 247–8
[7] Kockelman J and Hubbard M 2005 Bungee jump model with increasing strain-prediction accuracy *Sports Eng.* **8** 89–96
[8] Strnad J 1997 A simple theoretical model of a bungee jump *Eur. J. Phys.* **18** 388–91
[9] Calkin M and March R 1989 The dynamics of a falling chain *Am. J. Phys.* **57** 154–7
[10] Schagerl M, Steindl A, Steiner W and Troger H 1997 On the paradox of the free falling folded chain *Acta Mech.* **125** 155–68
[11] Tomaszewski W and Piernaski P 2005 Dynamics of ropes and chains: I. The fall of the folded chain *New J. Phys.* **7** 45
[12] Tomaszewski W, Piernaski P and Geminard J-C 2006 The motion of a freely failing chain tip *Am. J. Phys.* **74** 776–83
[13] Wong C and Yasui K 2006 *Am. J. Phys.* **74** 490–6
[14] Kagan D and Kott A 1996 The greater-than-*g*-acceleration of a bungee jumper *Phys. Teach.* **34** 368–73
[15] www.darylscience.com/Demos/Bungee.html
[16] Biezeveld H 2003 The bungee jumper: a comparison of predicted and measured values *Phys. Teach.* **41** 238–41
[17] Dubbelaar N and Brantjes R 2003 De valversnelling bij bungee-jumping (Gravitational acceleration in bungee jumping) *Nederlands Tijdschrift voor Natuurkunde* **69** 316–8
[18] Pasveer F and de Muynck W 2003 Wat is het verrassende aan bungee-jumping (What is surprising about bungee jumping?) *Nederlands Tijdschrift voor Natuurkunde* **96** 394
[19] www.itforus.oeiizk.waw.pl
[20] Heck A, Kędzierska E and Ellermeijer T 2009 Design and implementation of an integrated computer working environment *J. Comput. Math. Sci. Teach.* **28** 147–61
[21] Heck A and Ellermeijer T 2009 Giving students the run of sprinting models *Am. J. Phys.* **77** 1028–38
[22] D'Anna M 2006 Modeling in the classroom: linking physics to other disciplines and to

real-life phenomena *Modelling in Physics and Physics Education, Proceedings GIREP Conf. 2006* ed E van den Berg, T Ellermeijer and O Slooten (Amsterdam: University of Amsterdam) pp 121–36 www.girep2006.nl/
[23] Mols B 2003 Een gevoelige snaar: Veltman vs Dijkgraaf (Touching the right chord: Veltman vs Dijkgraaf) *Natuurwetenschap Techniek* **71** 18–25
[24] Sismanoglu B, Germano J and Caetano R 2009 A utilização da filmadora digital para o estudo do movimento dos corpos (Using the camcorder to study bodies movement) *Revista Brasileira de Ensino de Física* **32** 1501
[25] Teodoro T 2006 Embedding modelling in the general physics course: rationale and tools *Modelling in Physics and Physics Education, Proc. GIREP Conf. 2006* ed E van den Berg, T Ellermeijer and O Slooten (Amsterdam: University of Amsterdam) pp 66–77 www.girep2006.nl/
[26] Heck A and Ellermeijer T 2010 Mathematics assistants: meeting the needs of secondary school physics education *Acta Didactica Napocensia* at press

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