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# Introduction to relativity: a multi-level, multi-media resource.

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**Introductory university and senior high school physics syllabi often include Special Relativity, which poses conceptual problems and the difficulty that few of its effects may be directly observed with simple apparatus. We developed a web-based, multimedia resource (http://www.phys.unsw.edu.au/einsteinlight) that introduces and explains several of the key ideas at different but interconnected levels. The simple, introductory level uses film clips, animations and a few demonstrations to present the main ideas and logical development. Hyperlinks to supporting and explanatory pages allow students to delve more deeply into the difficult ideas.**

## Introduction

Syllabus authorities are faced with problems when attempting to modernise the syllabus with the inclusion of physics developed in the last century or so. For instance, it is difficult to discuss quantum mechanics or superconductivity without an understanding of wave behaviour. Many of the main aspects of special relativity, on the other hand, require only a modest background of other physical principles. So relativity has been included not only in introductory university courses, but also in various high school physics syllabi.

The difficulty, of course, is that relativity is difficult. And difficult in an odd way: the ideas themselves are simple, but they lead to counterintuitive results. A simple presentation always seems a little like sleight of hand: the ideas are simple and, with the exception of the invariance of the speed of light, nicely intuitive. Yet the results are unexpected and strange. One cannot help looking to see where the trick has been pulled.

To learn relativity, a few things are helpful. First, it is important to see that it is necessary: that Galileo's relativity and Maxwell's electromagnetism do not simply fit together. Second, one should be exposed to the perspective from which Einstein's principle of relativity (whence the invariance of c) is a reasonable, logical extension of Galileo's principle of relativity, and therefore not necessarily counterintuitive. Third, and most importantly, one needs further levels of explanation and supporting argument for many of the steps in the development.

When New South Wales' Board of Studies introduced its new high school syllabus, the School of Physics at UNSW introduced a suite of resources (http://www.phys.unsw.edu.au/hsc) covering a range of topics in the syllabus topic areas, including several web pages on aspects of special relativity.

In 2005, we made a major revision. That year, the International Year of Physics celebrated among other things the centenary of special relativity. In June 2005, one hundred years after Einstein submitted the famous paper, we launched *Einstein Light: relativity in brief or in detail*.

We made a decision to concentrate on presenting and explaining the physics of relativity. The NSW high school syllabus concentrates more on the history and social studies but we reasoned that these aspects were easier to understand from traditional resources. Further, we have no professional expertise in these aspects.

The use of the web for *Einstein Light* offers several advantages. One is the possibility of film clips and animations. Many of the effects central to the development of Special Relativity simply cannot by observed without rather elaborate equipment. In an animation, one can 'slow light down' to a convenient speed on the screen and cartoon characters may be happily accelerated at rates that would evaporate a human. Further, different points of view can be presented side by side for comparison. Finally, the interactive presentation is flexible and self-paced.

**The structure – branching hypertext for detail and support**

A major pedagogical advantage of the web is the branching structure possible using hypertext. In a streamlined, simplified presentation of a complex topic, one inevitably glosses over some details. In multimedia and hypertext, links can be given to explanations and supporting information that are either broader or deeper or both. *Einstein Light* comprises six multi-media modules that use film clips and animations, but it also has a few dozen supporting HTML pages (HTML, probably the most broadly used language on the web, stands for HyperText Mark-up Language).

The writer of *Einstein Light* (JW) has experience in teaching introductory relativity both to university to students and to curious members of the public. The producer and animator (GH) is the web master in the School of Physics at UNSW, and has experience in producing learning objects for the web, using a variety of softwares. The two had collaborated previously in a number of smaller projects.

*Einstein Light* was designed in two stages. The scope was to begin describing relative motion as understood in Galilean and Newtonian mechanics and some relevant parts of electricity and magnetism, then to continue through time dilation, length contraction, $E = mc^2$ and some of their applications. In the introductory level, our aim was to cover this argument, without leaving out any key steps, in no more than 10 minutes. (This calculation does not include the replays of modules or animations that most users are expected to use.) The next stage was to support this short version extensively with material at a range of different levels.

Originally, the range of supporting materials was suggested by experience: the writer recalled the questions that are usually asked, tried to foresee others, and then provided web pages to answer these. In several cases, these supporting pages were adaptations of pages that had already been developed by the authors for the purposes of teaching introductory relativity at university level. Once the writer-producer collaboration began in earnest, however, the producer provided much of the immediate feedback, asking questions or identifying points that were insufficiently clear and thereby suggesting need for revisions or for further material.

**The development: Galileo – Maxwell – Einstein**

The decision to begin with Galilean relativity was made because Galilean relativity is not self-evident to everyone. After all, if Aristotle could not understand it, it is not surprising that Galilean relativity contradicts the common sense of many. So *Einstein Light* gives examples of projectile motion under Galilean (Newtonian) relativity in animations that show the effect of relative motion, and that distinguish inertial and non-inertial frames.

Under pedagogically ideal situations, the use of animation for these topics is perhaps questionable. After all, projectile motion is moderately easy to observe directly. So of course the supporting pages offer experiments that students may perform for themselves in relative safety. Nevertheless, there are advantages in slowing down the motion and in offering, in proximity on the screen, the perspectives of two observers in relative motion. Further, the animations are less dangerous than might be, for example, the conducting of projectile experiments in non-inertial frames by enthusiastic students.

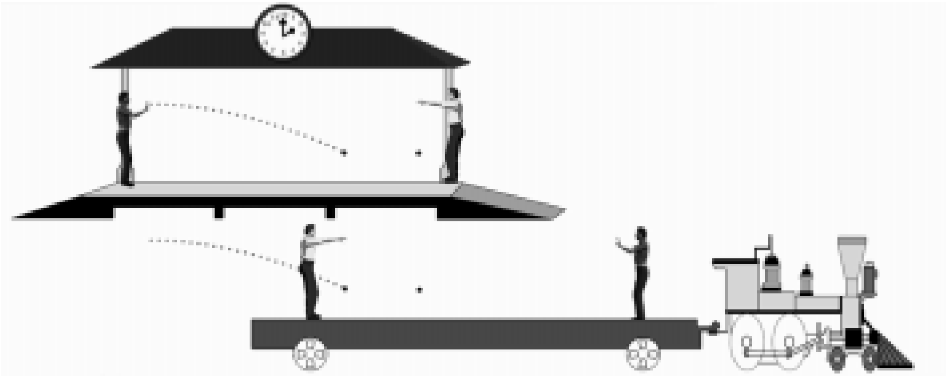

Fig1. A still from an animation of Galilean relativity, used on Einstein light. Figures on the platform throw and drop balls respectively, while those on the train drop and throw them.

We introduce electricity and magnetism next, because it is the apparent incompatibility between Galilean relativity and electromagnetism that makes Einstein's relativity necessary. Two simple demonstrations are shown as film clips. The repulsion between like charges is something that, in principle, one can do in the classroom. (In practice, however, due to some law related to Murphy's, it always seems to rain when one reaches electrostatics.) The demonstration of the force between two parallel wires, on the other hand, is one to be performed only with considerable caution: in order to obtain a clearly observed force over a separation of several centimetres, we use currents of hundreds of amperes. Again, the film clip is safer.

This revision allows us to do a nice *Gedankenexperiment*[1] that is often illuminating to students – the force between parallel moving charges. Here one can simply show that, under the principle of relativity, observers in relative motion will need to make corrections when comparing some physical quantities. This is a key point to accept: two competent physicists, using the same laws of physics will disagree on the measurements of some physical parameters from their different reference frames.

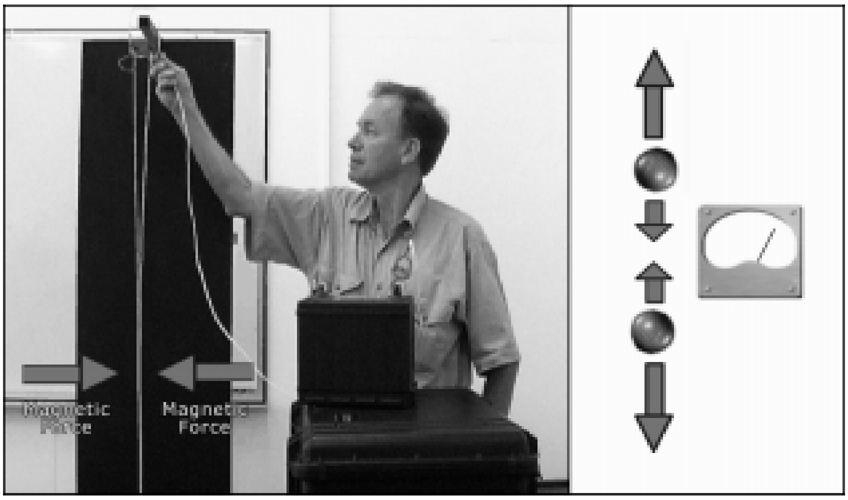


Fig 2. In this film clip (still at left), the magnetic force between initially parallel wires is shown. This illustrates the *Gedankenexperiment* at right concerning the force between moving charges (right).

The need for a resolution is now established, so it is time to look at how Special Relativity provides this. Einstein's principle of relativity is introduced as a simple, logical extension of that of Galileo. Logical, yes. Simple, yes. But easy, no. Perhaps the biggest conceptual problem in Special Relativity is the invariance of the speed of light c between observers. It obviously

[1] Gedankenexperiment or 'thought experiment' is a term coined by Ernst Mach. It means the imagining of what a theory would predict in a hypothetical case. Although potentially misleading – the term often refers in physics to cases that are difficult or impossible to achieve – its use by Einstein has given it wide currency.

contradicts the simple vector additivity of velocities that seems so intuitive in Newtonian kinematics.

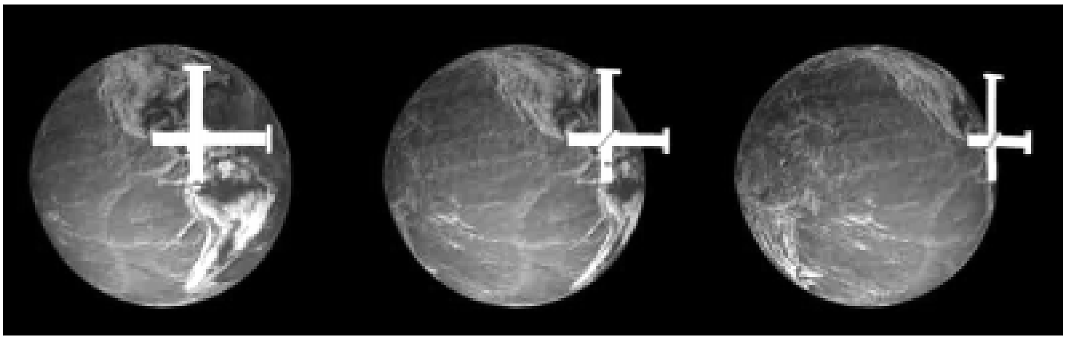

Fig 3. Frames from an animation of the Michelson-Morley experiment.

In teaching relativity, it is never enough to quote results of experiments, however precise and oft repeated they have now become (eg Antonini et al, 2005). Intuition is strong and an almost inevitable response to the non-additivity of velocities is "it just can't be". Instead, one can try to make the invariance of c intuitive also. So we provide web pages that do this at different levels, first qualitatively, then by looking at the various symmetries that appear in Maxwell's equations. Nevertheless, it is important not to try to make this look simple – because it is not. Everyone entering relativity should be reassured that virtually every physicist found it – and often still finds it – weird, counterintuitive or even disturbing.

From the invariance of c to time dilation is straightforward, using the standard geometry of a light pulse travelling at right angles to the relative motion, as measured by one observer. Length contraction and the relativity of simultaneity then follow simply. These are supported by a series of animations with stop-action buttons that allow the user to check that, in the viewpoint of each observer, light appears to travel equal distances in equal intervals of that observer's times. Because they are so much fun, special pages are devoted to the twin paradox and the pole-in-the-barn paradox.

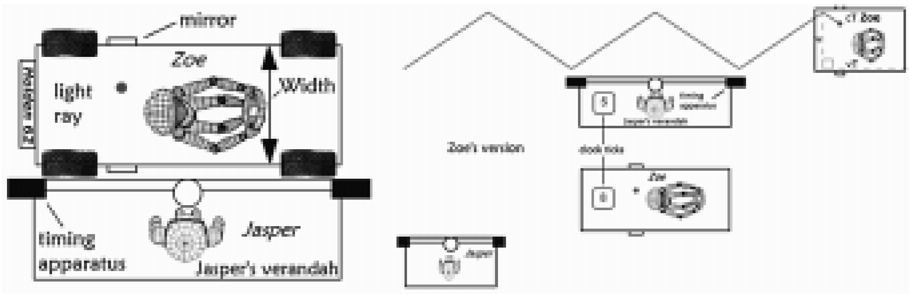


Fig 4. Stills from animations using the classic Pythagorean geometry to derive the expression for time dilation.

At the presentation level of *Einstein Light*, the derivation of relativistic dynamics is presented only superficially. It is reasonable that, if observers disagree on distances, times and accelerations, they will also obtain different values for the work done. (The relativistic version of the work-energy theorem is presented as a supporting page.) The results, including of course the famous equation for the proper energy, are presented in a series of animations.

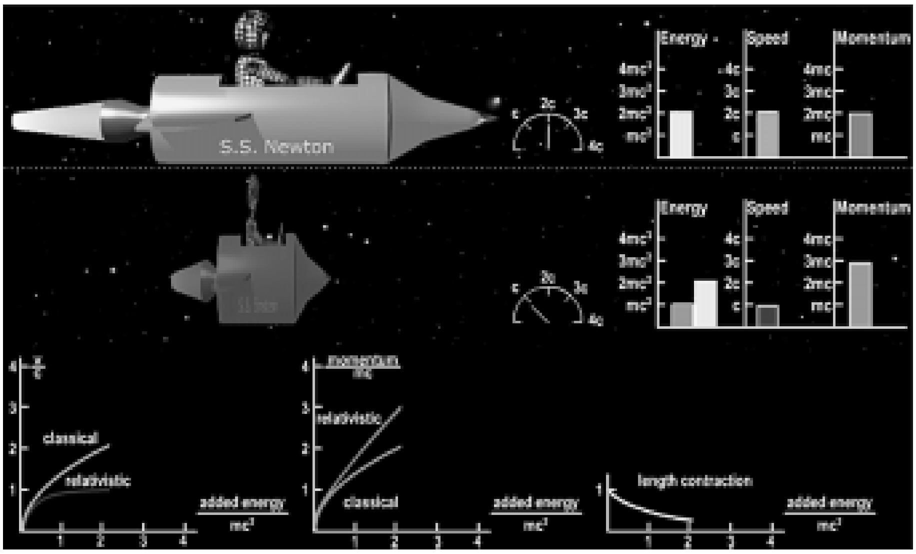


Fig 5. Stills from an animation comparing Newtonian and relativistic dynamics.

To show that relativity is not just an obscure bit of physics, but also part of mainstream engineering, we cite several examples. In the Global Positioning System, the relativistic _ factor is only slightly different from one, but the accuracy of this system would be impossible without relativistic calculations. On the other hand, in the accelerators used to treat cancers in hospitals, _ may be about 200 – to use Newtonian mechanics here would give errors of 20,000%. Again, supporting pages consider other applications and consequences. Finally, a brief section called 'Beyond Relativity' mentions General Relativity, considers the difficulty of reconciling general relativity with quantum mechanics at the Planck scale and mentions some current research directions.

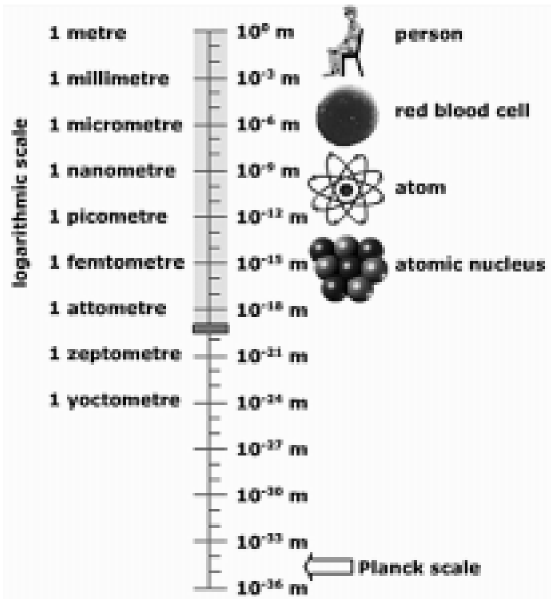


Fig 6. Still from an animation using a log scale to illustrate the Planck length.

Because of our decision to concentrate on physics rather than history, we base the treatment mainly on just a few of the most important original sources (Galileo, 1632; Einstein, 1905a&b; Einstein, 1912) and we mention only in passing the developments by others that predated Einstein's relativity. A larger set of references is given in one of the supporting web pages, however, and it gives links to further material. (The sound file of Einstein describing his most famous equation is one of our favourites.)

The main page links directly to a summary that shows the logic of the presentation. A quiz, with questions covering a moderate range of difficulty, allows the user to test his/her understanding. Two of the questions, added later, were supplied by users of *Einstein Light*. Both are in the form of paradoxes. Each of the correspondents sincerely believed that he had developed a paradox that showed an internal flaw that fatally damaged relativity, and urged us to be brave enough to publicise them on the web site, whether we could answer them or not. As it happened, the material required to resolve the paradox was already on the supporting material, so they make rather good quiz questions.

**The presentation style**

For the multi-media modules, we elected to use film clips and animations with voice-over. The presentation begins and ends with a talking head, a little like a lesson. In several cases, video clips of demonstrations were possible. However, one of the problems with relativity is that most of the effects are difficult or even dangerous to film. Hence the animations.

Several of the reviews of *Einstein Light* have mentioned the 'quirky' animations. Two low-resolution humanoid figures take the roles of the two relativistic observers, and seem to suffer no negative consequences from being accelerated to relativistic speeds and back again.

The use of voice-over makes for a natural presentation, but disadvantages the non-Anglophone. We tried to counter this in two ways. First, there are English subtitles, because ESL speakers are often aided by simultaneous presentation of text and voice. Second, there are subtitles in a range of modern world languages, selected largely by our own contacts. (We are still seeking an Arabic-speaking physicist to help with that project.)

**Writing, production and creating**

Educational technology is affecting the way in which teachers view and comprehend their role in the process of helping students learn. McCann et al (1998) sum up their findings for staff at higher education institutions in Australia by stating that the "use of communications and information technologies in university teaching and learning changes traditional teaching roles through a new focus on teaching and learning teams and instructional designers". *Einstein Light* depended on teamwork. The writer had one set of constraints – starting with the injunction, commonly attributed to Einstein himself, that "everything should be made as simple as possible, but no simpler". The producer/animator was more interested in producing something that was engaging and attractive, within the limitations of the software available and bandwidth considerations. An understanding and appreciation of one another's roles has allowed a flexible creative process. The positive feedback concerning the final product is an indication that this process has produced something far better than either could have managed alone.

The development of *Einstein Light* involved as much evolution as it did planning. The initial idea was to create a series of short film clips that would present the main theme, while providing links to existing or new material at key points, and this guided the original script. The idea to bind this together with a 'train' theme came from the producer (GH). Writer and producer then worked closely and interacted to revise the script to make best use of the animations. The contiguous representation of the audio and visual material (subtitling, pictures, animations and video) provides the type of coherent rich-media environment that Mayer and Moreno (1997) refer to as fulfilling the requirements of the "Multiple Representation Principle".

**The techniques.**

The animations and multimedia modules are Flash based and embedded in a traditional HTML environment. Each multimedia module is reproduced with an equivalent HTML page, for the benefit of those with very slow connections or the vision-impaired using text-to-speech. The embedding of video within the Flash environment is a technique that allows overlays and animations to be used simultaneously with the film clip to illuminate and to clarify further the difficult material (Examples are the film clips in the Maxwell module used to review aspects of electrostatics and magnetism).

3D characters and props were generated using the software packages Poser and 3D Swift respectively, and then imported to the Flash environment. Although the final result may appear daunting to the novice, both software packages come with characters, poses and props already configured thus allowing the user to tap into much of the power of the programs rapidly and easily. Jerky motion of some of the animations is due partly to the fact that frames were omitted to reduce bandwidth – but perhaps also to the inexperience of the animator. As we never aim to hide the fact that the figures are animated, this is only a minor worry.

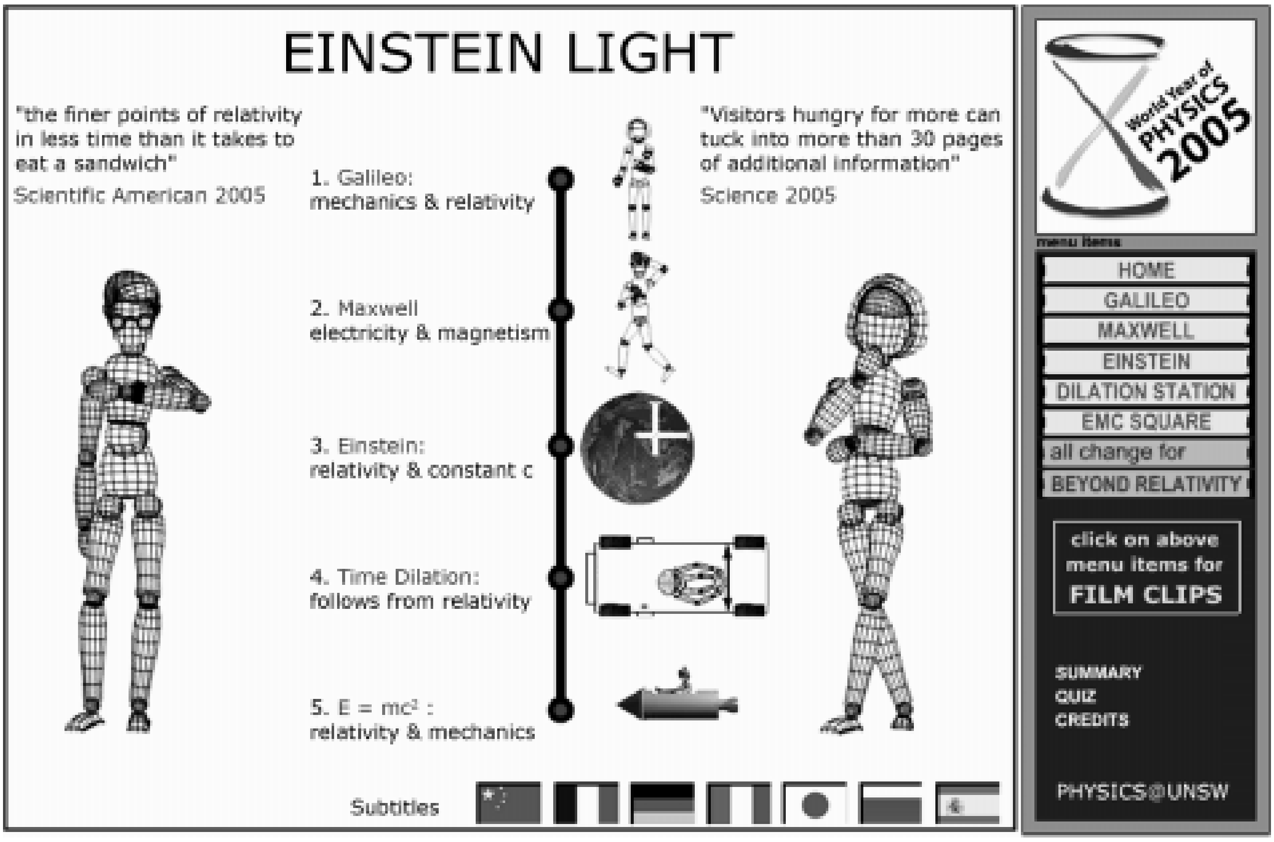


Fig 7. The top of the splash page of *Einstein Light*.

The use of the more advanced features of the Flash environment was deliberately minimised: programming was limited to basic button functionality and to animation effects that required at most a few lines of simple code. Each of the main modules includes a series of animations or re-usable, multimedia learning objects. Once these were created, the main tasks were synchronising, embedding and compression.

One significant cost in multimedia development of this sort is the time that must be invested. Clark and Mayer (2003) state that "Experienced multimedia developers acknowledge that it takes from ten to twenty times more labor and skill to produce good courseware for e-learning than for traditional class-room materials". This factor may be decreased as the developers become more skilled in use of the media, but it will always be considerable. Against that may be offset the economies of scale: presentations that are used by hundreds of thousands of users around the world may merit substantial input. The learning objects have the advantages, too, of being versatile and re-usable. And there is also the advantage that web objects are easier to locate and to adapt – even for the creators – than are materials in filing cabinets.

Various organisations, including of course software companies, run workshops for teaching multimedia development. For educators seeking to produce such learning objects, however, there is the problem that many such workshops are aimed at those who intend to use the software for commercial use, such as professional film and video animation. On the other hand, much can be achieved using only a small, simple subset of the software's capabilities. For the purpose of education, it would probably be more useful to conduct some workshops that aim to make the educator or the technical support staff comfortable with a small set of tools and features that would be most relevant in a teaching environment. Nevertheless, our experience suggests that one should plan for a substantial investment of time, aim for only moderate and necessary complexity and to concentrate on the content and the pedagogical effect ahead of technical professionalism.

## Conclusions and reactions

Producing *Einstein Light* has been an interesting task for a physicist and an IT/education specialist working together. Especially because of its mode of delivery, it is very difficult to assess its educational effect objectively. However, the resource has won awards and been praised by a number of reviews, from *Science* to *The Sydney Morning Herald*, from *Scientific American* to *Yahoo* and is visited by hundreds or thousands of unique visitors each day. One of our favourite quotations comes from the UK's *The Sunday Times*. Listing *Einstein Light* as one of its top ten picks of web sites for 2005, its reviewer wrote: "Here, Einstein is made simple not by dumbing down, but through clear explanations that transform complex physics into manageable lessons. More ambitious sites should take note that swish graphics are not always the answer: content tends always to be king."

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