MODELING PHYSICS

SYSTEM DYNAMICS IN PHYSICS EDUCATION

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Conceptual learning

Physics is a heap of formulas; when you want to solve a problem you just have to choose the proper equation, fill in numbers, and calculate the missing value.

Many students share this view about physics — at least about physics instruction. On the other hand physicists rightly claim that the power of physics lies in describing a great variety of phenomena by a very limited set of fundamental laws and principles. Students often fail to make distinctions between the *power tools* of physics (as Macdonald, Redish & Wilson[2] call them) and the *gimmicks*, e.g. functions describing special forms of motion. Fundamental laws like $F=m\cdot a$ are considered as *just another equation* of the same quality as $s(t)=1/2gt^2$ (for the free fall of bodies). One of the reasons is that physics instruction puts too much weight on the *gimmicks*, e.g. when typical textbook problems concentrate on solving equation systems and calculating numbers.

System dynamics modeling can help to shift the focus towards more qualitative conceptual learning. Modeling physical phenomena means applying the fundamental concepts and laws and leaving the tedious task of solving equations to the computer. Dynamic modeling requires the students to analyze a phenomenon and develop the model *him- or herself*. The students are introduced into the strategy of expert problem solvers, i.e. to concentrate on a conceptual and semi-quantitative analysis. Before special functional relationships can be used in STELLA-models, the relevant quantities have to be defined and the structure, i.e. the *conceptual features* of the model, must be formulated. The physical assumptions are completely explicit in the graphical model structure. The modeling system supports the learner both in constructing the model and exploring its physical adequacy through simulation runs.

The conceptual structure of force & motion

Models within a certain domain of physics have a common core structures that visualize the power tools. Models about force and motion e.g. contain the chain force→momentum→velocity→position as shown in Figure #1. The core model is based on Newton's second law ($F(t)=\Delta p/\Delta t$) and the definitions of velocity ($v(t)=\Delta s/\Delta t$) and momentum ($p=m\cdot v$).

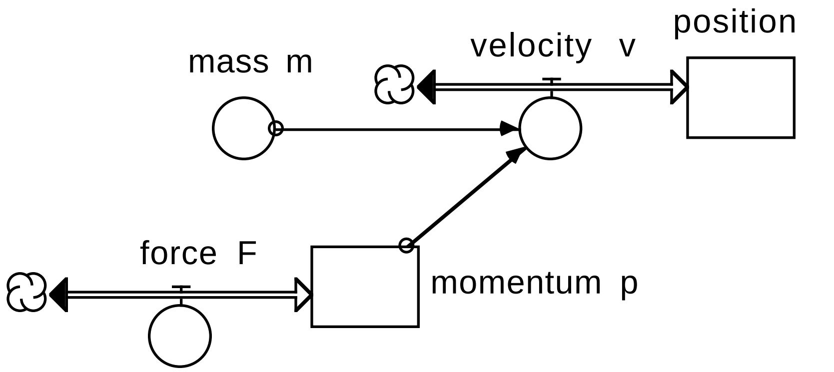

Figure #1 Core structure of force & motion models in mechanics. The net force F exerted on an object causes a change of its momentum $\Delta p=F\cdot\Delta t$ (Newton's second law). The object's velocity is given by $v=p/m$. The velocity acts as the rate of change of position s: $\Delta s=v\cdot\Delta t$.

The basic structure is easily reproduced by students for new problems. Physical pondering can concentrate on the question *which forces are exerted* on the body in a given situation. The forces can either be constant (e.g. weight), or depend on position (gravitation), velocity (friction) and even time, but always the principles of Newtonian mechanics are clearly visualized. The same basic model applies for pendula, parachutists and planets as well as for charged particles in a mass spectrometer. You only have to work out which particular forces act in the particular case. Other core structures exist for electromagnetism or radioactive decay. Students learn that physics is "easy"—in the sense that many different examples can be explained with the same small set of conceptual instruments.

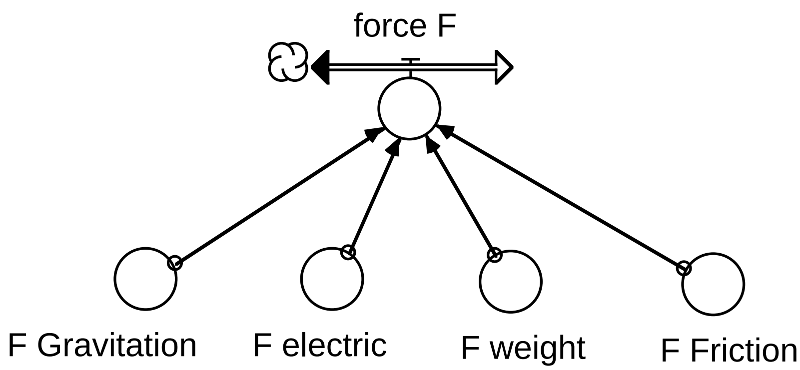

Figure #2 The main question in building models in mechanics is: Which single forces are acting on the body and sum up to the net force F?

The motion of meteors

For students in mechanics classes one of the most interesting applications of the Newtonian structure was the motion of meteors in the atmosphere of the Earth. The model in Figure #4 describes this phenomenon. The teaching unit starts with measuring the motion of paper cones dropping from the ceiling. The effects of velocity, shape, cross section area and air density on friction are described semi-quantitatively. Afterwards the students look up the functional relationship between drag and these quantities in the textbook.

The next step lies in modeling the motion of a parachutist (see Figure #3). The students are familiar with the dynamic core model from earlier examples. They concentrate on modeling the drag force and assessing realistic values for the parameters, like the cross section of an open parachute. Group work on this model does not take more than one lesson.

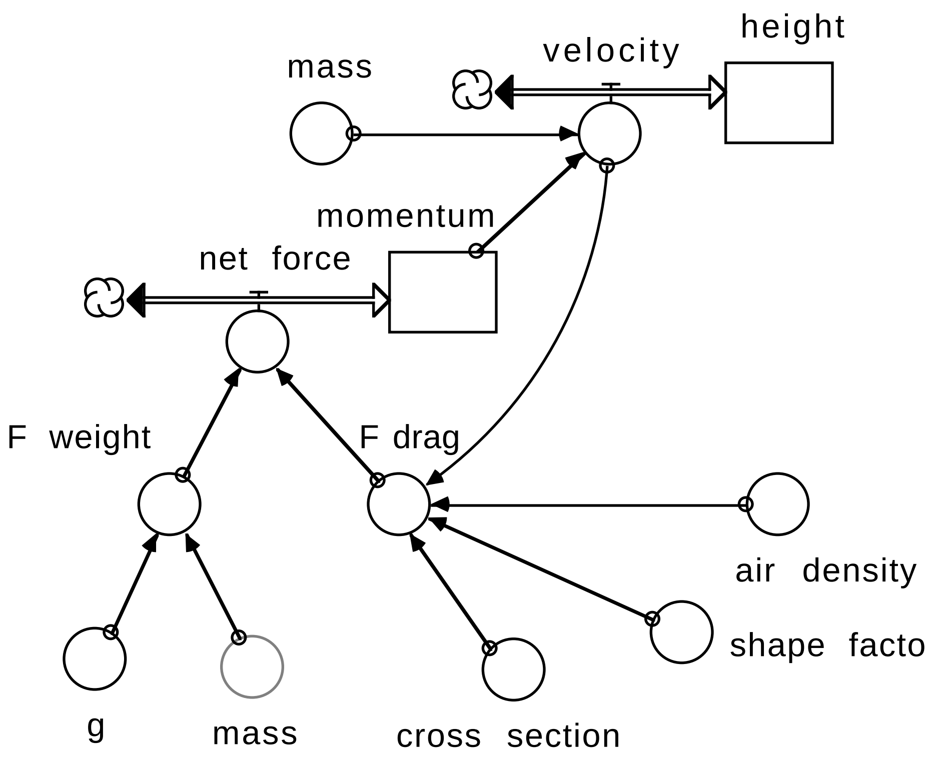

Figure #3 Parachuting. The upper part of the model consists of the force & motion core model. Two forces act on the parachutist: weight and drag. The feedback loop from velocity to drag demonstrates that drag increases with velocity (drag$\propto v^2$).

The parachute model can easily be adapted to the fall of a meteor in another unit of group work. Although this phenomenon seems to be quite different, only a few changes are necessary. Mainly a second feedback loop has to be added that runs from *height* to *air density*. In the parachute model air density can be considered as a constant. Now the change of air density with height becomes a central feature. With STELLA this relationship can be defined by a graphical converter using data from a corresponding table in a handbook. Although the model simplifies the motion—in that it is only one-dimensional—the major effects can be studied. The meteor enters the atmosphere with super-terminal velocity. In order to plot the brake deceleration, the function for acceleration is added to model (a=F/m).

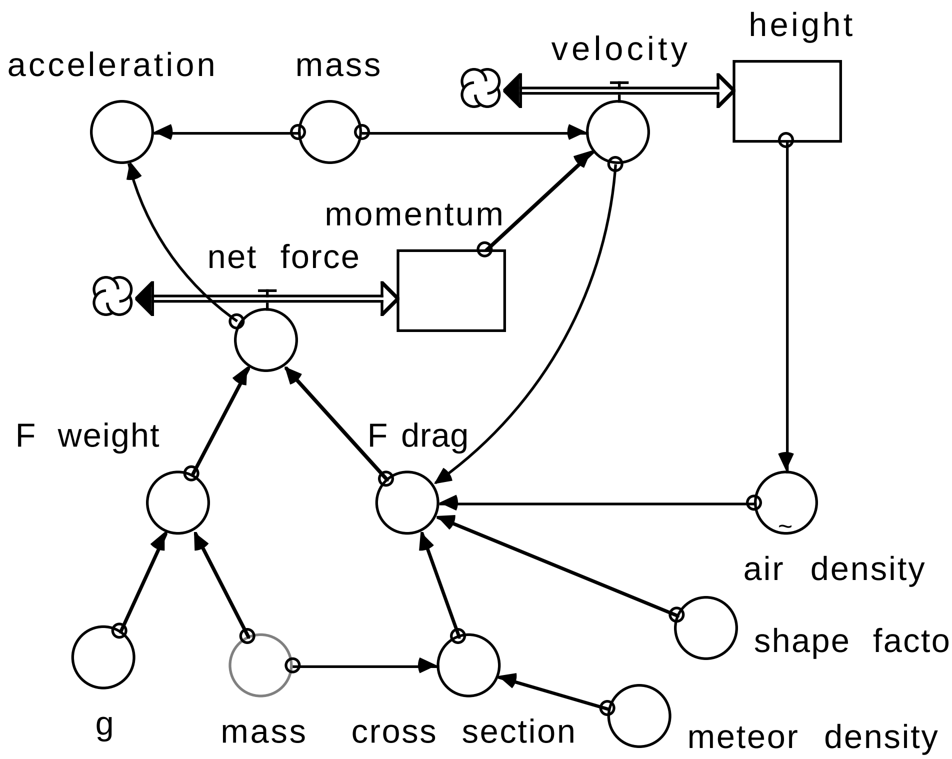

Figure #4A STELLA model of a meteor fall.

The standard structure is applied with two forces (weight and drag). Two feedback loops run from velocity to drag and from displacement via air density to drag. Mass and density of the meteor are modeled as separate parameters to calculate cross sections for different types of meteors (iron, stone).

```
height(t) = height(t - dt) + (velocity) * dt
INIT height = 100000 {m, approx. border of the atmosphere}
INFLOWS:
    velocity = momentum/mass
momentum(t) = momentum(t - dt) + (net_force) * dt
INIT momentum = -10000 {m/s; meteor velocity}*mass {kg; meteor mass}
INFLOWS:
    net_force = F_weight+F_drag
acceleration = net_force/mass {m/s^2}
cross_section = (3*mass/(4*PI*meteor_density))^(2/3)*PI
{m^2; cross section can be calculated for differen types of meteors: ston iron}
F_drag = - 1/2*cross_section*air_density*shape_factor*velocity*ABS(velocity)
{air friction: F~v^2, anti-parallel to velocity}
F_weight = mass*g {N; considered to be approx. constant}
g = -9.81 {m/s^2 (at zero height)}
mass = 500 {kg}
meteor_density = 8000 {kg/m^3; iron (stone: 3500 kg/m^3)}
shape_factor = 2
air_density = GRAPH(height
```

Figure #4B Equations of the meteor model. Data for the graphical converter air_density=GRAPH (height) can e.g. be found in the Handbook for Physics and Chemistry.

Before the model is tested in a simulation run, the students should be prompted to make predictions for the v(t) and a(t) graphs they expect. The graphs actually produced by the model are surprising. Figure #5 shows graphs for three types of meteors. For understanding the shapes of the v(t) and a(t) graphs it takes an effort to discuss the contrary effects of decreasing velocity and increasing air density on drag. Instead of a monotonic tendency the acceleration has a peak with maximum of several hundred g (see Figure #5A). This graph illustrates why most meteors melt away in the atmosphere under the influence of high friction forces. The velocity of the stone meteor (Figure #5B) nearly decelerates to zero before it reaches the ground. The big iron meteor hits the Earth with an enormous impact. This explains why only medium size meteorites can be dug from the soil: The small ones melt in the atmosphere and the big ones evaporate on hitting the ground.

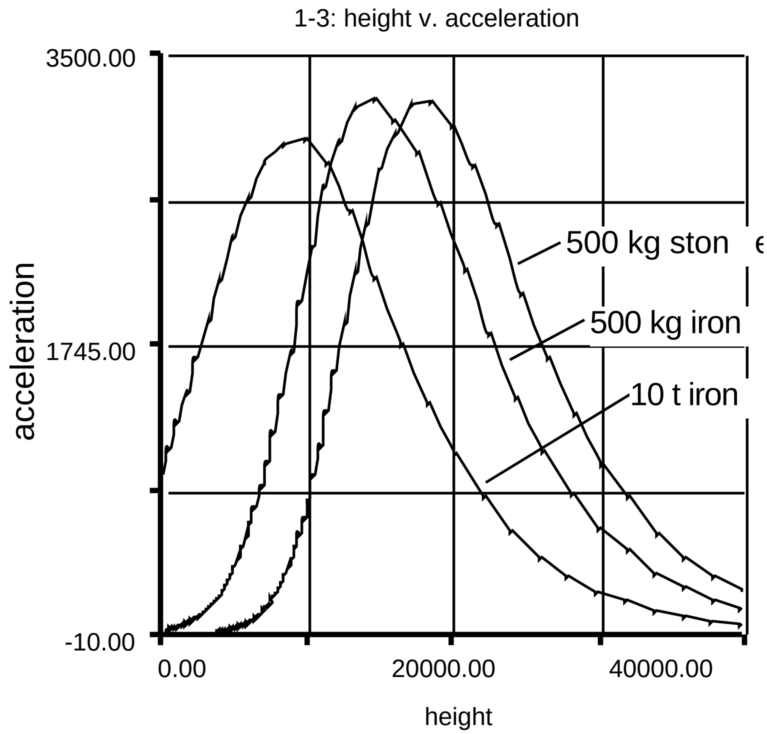

Figure #5A Deceleration of different types of meteors predicted by the model. Values of several hundred g are reached (compare: -10 m/s^2 = 1 g is the acceleration of a free falling body).

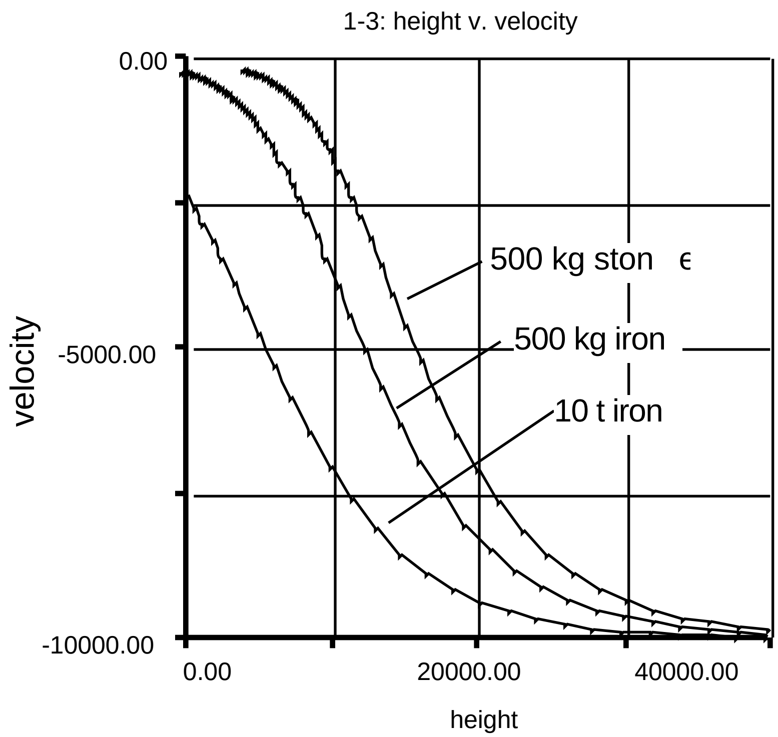

Figure #5A Velocities of different types of meteors. The stone meteor slows down from -10,000 m/s at a height of 40,000 m to nearly 0 m/s at ground level. The big iron meteor still has an enormous kinetic energy when it hits the ground.

One of the reasons why the students found the meteor unit so stimulating was that—as a student put it—"one did not know what comes out". The phenomenon is too complex for a quick estimation. In conventional instruction *mathematical* boundaries limit the set of investigations for school physics because of the need to use calculus. In school mechanics bodies move with uniform velocity or with uniform acceleration because under these assumptions the 'laws', rather the 'equations', of motion become relatively simple. The differential equations can be solved with a limited amount of algebra and calculus. The motion of parachutists is not examined because it is too 'difficult';

which means that the equations cannot be solved on school level. System dynamics tools break down these boundaries and extend the scope of instruction far beyond the physics of air tracks and vacuum pipes.

Projects at the University of Bremen

The fact that system dynamics modeling is a context-free tool for many domains of physics and allows students to build their own physical models was the starting point for the *Computers in Physics Education Group*[3] at the University of Bremen to engage in development and research in the area of computer aided modeling in 1988. At that time we browsed through a great number of ready-made simulation programs already available. They tended to be limited to single specific phenomena; the theoretical assumptions that went into the source code were not made explicit, and the prerequisite for realizing own ideas afforded the students to learn a programming language. When we accidentally came across STELLA we were stunned by its power. There it was: the multi-purpose, open-ended, and user-friendly tool we had waited for.

From 1988 to 1992 a pilot project "Computers in Physics Education" at the University of Bremen received a federal grant. The project developed teacher-training materials with a large selection of models for various domains like mechanics, oscillations, electrodynamics and radioactivity. The materials were field tested in high school physics courses in the State of Bremen (students aged 16 to 19). The courses frequently worked with STELLA over a period of 6 months up to three years. A follow up project spread the ideas to other states of the Federal Republic of Germany and to other subjects like mathematics and biology.

Standard examples for dynamic modeling in an 11th grade mechanics course (students aged 16 to 17) are:

- Kinematics:
  - bicycle race (uniform motion),
  - free falling bodies (uniform acceleration)
  - shot-putting (two-dimensional motion)
- Dynamics:
  - motion of a parachutist
  - a meteor enters the atmosphere
  - goalkick (friction forces in two dimensions)
- Work: stretching a rubber band
- Momentum: launch of a toy-rocket

In an advanced level physics course these units cover about 30% from a total of 80 lessons in 5 months, including experiments, calculations and modeling. Computer usage both in group work and in the class forum is limited to about 10% of the course time. This shows that computer-based modeling *does not replace* deductions, experiments or calculus-based approaches. Instead it rather *enriches* the spectrum of methodological means.

It works

From evaluating long-term case-studies in several schools we found that system dynamics in physics *works*—in the sense that students actively engage in modeling in small groups and that interesting new examples can be dealt with in class. In an interview a student said after five months of working with STELLA:

> *"In the beginning the computer was a bit too much in the foreground. The question was: How does STELLA work? This may have been necessary because the computer had to be explained to the class. But now it just works, because most of the people have got it. Together we think about the problem, and then - bang - the inputs are made. That is no problem anymore. It just was in the beginning, when we had to learn it a bit."*

The evaluation gives evidence that the modeling system really served the students as a *tool* for solving physical problems. When students failed to arrive at a proper model, the reasons in most cases did not lie in the system dynamics approach but in the more complex cases which posed a greater physical challenge.

We found that the use of modeling systems improves the opportunities of students to formulate goals for own physical investigations and to follow individual paths to solutions—provided that the overall teaching strategy is in accordance with the *constructivist principle* of open-ended learning environments in which students can bring in their own ideas (cf. Forrester's idea of learner-directed learning[4]).

What we do want to know more about is *how* making models fosters the development of physical understanding. Our hypothesis is that the equivalence of graphical STELLA-model structures with the basic theoretical structures, e.g. in Newtonian dynamics, forms an additional *input channel* for physical theory, complementary to equations and descriptions in sentences. Furthermore the need to decide whether a physical quantity is a *rate of change* or a *state* variable often triggers interesting discussions in class that deepen the understanding of physical quantities like *current* (rate of change of *charge*) or *energy* (state variable, effected by the rate *power*). But we also know that not all of the students profit from system dynamics modeling. Some cling to the 'formulas' and others feel overburdened because of the more complex examples.

Current research

In 1996 a grant from the German Science Foundation started a new research project on physical understanding by system dynamics. We want to analyze in depth what is going in students' minds when they work with a graphical modeling package. A second issue is the transfer of modeling competence from physics to non-scientific domains. The empirical studies are done in a high-school physics course (advanced level) over 2 semesters (mechanics and fields).

STELLA will also be used in a new research project funded by the European Community: *Labwork in Science Education*. Together with colleagues from France a joint task group works on integrating micro-based laboratories with computer-based modeling. The aim is to bridge the gap between experiment and theory by working on an experiment and a dynamic model in parallel. Experiments serve as empirical starting points for modeling, while modeling results stimulate new experiments or new ways of evaluating experimental data. One example is a close mapping of measurements from decay experiments with corresponding decay-models. The approach will be published in a new International Handbook of Science Education[5].

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[2] MacDonald, W.M., Redish, E.F.& Wilson J.M.: The M.U.P.P.E.T. Manifesto. In: Computers in Physics Education, July/August 1988, 23-30.

[3] Horst P. Schecker, Thomas Bethge, and Hans Niedderer.

[4] Forrester, J.W.: System dynamics as a foundation for pre-college education. Cambridge, MA: MIT, System Dynamics Group 1990.

[5] Tobin, K. & Fraser, B.J. (eds.): International Handbook of Science Education. Kluwer, The Netherlands (in preparation).