Learning Mechanics with Modelling Systems[1]

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Research questions

The field study[1] evaluated the effects of computer-based modelling on learning mechanics: Does the use of system dynamics modelling (SDM) software help students to develop a Newtonian view of the relationship between force and the change of motion? We also explored the transfer aspects: Does modelling in physics support the development of general capabilities to structure complex systems (systems thinking)? This report focusses on the first question.

In SDM students start with the interactive construction of a concept map that shows the relevant quantities and their relationships (see Schecker, 1998). Figure 1 shows the basic structure of all mechanics models. The concept map layer is an advanced form of representing Newtonian ideas in addition to formulas. As a second step, functions like $F = m \cdot g$ or $F = D \cdot x$ for weight or spring forces are introduced to adapt the basic model to a given situation. The computer solves the model equation system numerically and produces tables and graphs. As students do not need to solve it analytically, more complex and motivating problems can be dealt with. Examples are parachuting and the motion of meteors.

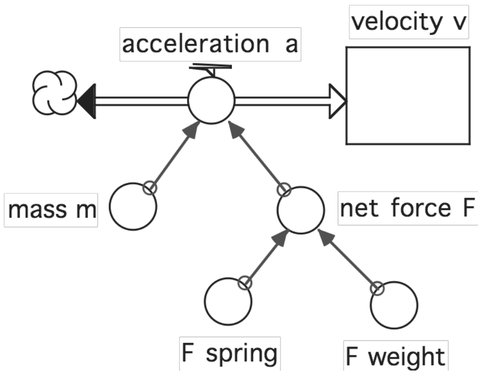

Figure 1: Core structure of force and motion models in mechanics. The net force F exerted on an object determines its acceleration which acts as a *rate of change* on the *state* quantity velocity (Newton's second law). Special single forces can be introduced.

Forrester (1990) assumes that SDM builds up systems thinking as a cross-curricular competence. Some studies report positive effects on students' understanding, e.g. of exponential growth and decay. Others are sceptical about students' grasp of the procedures that the software performs to produce the results. A review of literature is given by Doerr (1996).

Methods and sample

Our study[i] had a semi-experimental pre-post-follow up design. The experimental group consisted of 27 students in two upper-secondary physics courses (Gymnasium, Leistungskurse, 5 lessons per week, students aged 16 to 17). Over a period of 20 weeks they worked repeatedly with a graphics-oriented model building system (Stella) on phenomena in the areas of kinematics and dynamics. The teachers were experienced in applying SDM in physics courses. Two concurrently running physics courses (35 students) without computer-based modelling

[1] Paper presented at the Fifth International ESERA Conference on Contributions of Research of Enhancing Students´Interests in Learning Science. Barcelona, August 2005.

formed the control group (CG). The syllabus in the domain of mechanics is well established so that the physics content in all four courses was comparable. We made sure that all four teachers aimed at the same concepts and covered a common set of phenomena.
In the experimental group (EG), about a quarter of the teaching time was used for five modelling units including experiments and computer-based modelling. Students worked in small groups. The CG courses spent more time on teacher-centred classroom discourses and on formal quantitative tasks.

An extensive set of instruments was used to measure physics competence and systems thinking. The most important tests on understanding mechanics were:

- the Force Concept Inventory (FCI)
- interviews about motion
- model construction and interpretation tests

These tests were given at the beginning of the courses (pre), after 20 weeks of mechanics instruction (post), and again another 20 weeks later (follow-up). The pre-tests as well as an intelligence test carried out along with them showed no significant differences between EG and CG.
The *FCI* (29 multiple choice items; Hesteness, Wells and Swackhamer 1992) was used to compare the global learning effects of the two groups (Cronbach's alpha = 0.77). In particular, a subscale of seven items relevant for understanding Newton's second law was analyzed. Despite its reliability being rather low (alpha = 0.53), the scale was nevertheless evaluated as we expected specific effects in this central element of Newtonian dynamics.
The semi-structured *interviews about motion* consisted of three stages (Schecker and Gerdes 1998):

(1) The interviewer showed an experiment, e.g. the motion of a cart accelerated by a key-chain (force depends on position of the cart), and asked the student to describe the motion.
(2) The student sketched a velocity-time-diagram (paper and pencil). He or she was given 5 to 10 minutes time to ponder before presenting the results to the interviewer. If necessary the interviews asked students to include forces into their reasoning.
(3) If the solution was not appropriate, the interviewer introduced a poster with the Newtonian view on force and motion, and asked the student to re-consider his or her solution (only in post and follow-up interviews).

The quality of students' reasoning was rated separately for the three interview stages on an ordinal scale. The ranks were "no approach/mistakes in kinematics", "kinematics correct, but dynamics insufficient" and "kinematics and dynamics correct". Two persons rated independently (inter-rater-reliabiltiy: Kendalls $\tau_b \geq 0.8$).
The *model construction and interpretation test* was a paper and pencil method that led students through consecutive steps of constructing and interpreting formal descriptions of a given situation from physics or economics (transfer domain). It included qualitative parts (e.g. concept mapping) as well as quantitative tasks (equation-based calculations).

Data analysis and results
The parameters gained from evaluating the various tests form a rather complex picture.
The *FCI*-results do not support our hypothesis that the modelling approach leads to a better general understanding of mechanics. Neither the global post-test scores nor the profile analyses of the Newton 2-subscale show an advantage of the EG over the CG. The global post FCI-score in the EG is even lower (significant, Mann-Whitney U-Test, p = 0.09), while the pre-post gain in FCI compared to the initial state is higher in experimental course 1 (Hake factor g = 0.43; missing data in EG course 2) than in the two control courses (g = 0.38 and g = 0.24). An examination of students' mistakes revealed a state between impetus-ideas and Newtonian concepts in all four courses.

The *interviews about motion test* probe directly into semi-quantitative capabilities to apply Newtonian ideas for describing motion under the influence of forces. Students in the EG have significantly been more successful in the post test (Mann-Whitney U-Test, $p = 0.07$). 55% of the CG students failed to explain the key-chain experiment in the post-test compared to 27% in the EG (correct dynamic solutions: EG: 47%, CG: 30%). Follow-up results, however, do not reproduce this difference. The follow-up task was to describe the motion of electrons in an electric field (transfer within physics). Both groups reached equal scores.
The *model construction and interpretation tests* prove a higher gain in semi-quantitative modelling for the experimental group. Slight advantages of the CG-students in the area of quantitative model interpretation, e.g. in formal equation-oriented calculations, are not significant. In the EG there was only modest transfer of system dynamics modelling to other domains (contiguous transfer within physics: fields; remote transfer: economics). Only intellectually gifted students identified rate and state variables without longer periods of trial-and-error.

Conclusions and implications

The effects of teaching mechanics with model building systems are limited to semi-quantitative reasoning about motion. These findings are in accordance with the specific potential of system dynamics modelling to support a dynamic view of motion under the influence of forces. There is no overall positive effect on understanding mechanics. On the other hand, there is no trade-off between the ability to model physics phenomena conceptually and solving equation systems formally.
The assumption that system dynamics modelling develops as a transferable cross-curricular competence cannot be supported from our data. Systems thinking depends on a combination of modelling expertise with content-specific knowledge.
The study shows that computer-based modelling in mechanics is an appropriate way to include more complex phenomena in teaching mechanics and to help students develop a dynamic view of force and motion. It does, however, not remove the general problems of teaching and learning Newtonian mechanics.

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[i] Schecker, H. & Klieme, E.: Förderung physikalischer Kompetenz und systemischen Denkens durch computergestützte Modellbildungssysteme (development of physics competence and systems thinking through computer-based modelling). Bremen, Berlin und Bonn 1996-1999, supported by German Science Foundation (DFG), grants NI 271/9 and KL 1057/1.