Temporary title: Students' challenges with computational modeling of physics

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(Dated: 11th May 2010)

In later years, computational perspectives have become essential parts in several of the University of Oslo's natural science studies. In this paper I discuss some main findings from a qualitative study of the computational perspectives' impact on the students' work with their first course in physics – mechanics – and their learning and meaning making of its contents. Discussions relating to the students' learning of physics are based on the sociocultural theory, which originates in Vygotsky and Bakhtin, and subsequent physics didactics research. Results imply that the computational assignments' greatest challenge is their combined use of students' knowledge from earlier separated contexts. Making use of informatics, numerical and analytical mathematics and conceptual understanding of physics in one big package, appears as a clear challenge for the students. A lack of awareness considering the limitations of physical modeling is also observed. I argue in favor of helping the students create an awareness concerning their use of sufficient knowledge and system of conception, or "tool set", for the different tasks at hand. They need help creating a plan for their modeling and to become aware of its limits. In light of this, I propose a specific and dialogic text as grounds for the exercises, in which stress is laid on clarification and elaboration, to be of potential great aid for the students.

I. INTRODUCTION

Both computers and the great span in numerical methods for mathematical computations have gradually evolved due to scientific research with its endless stream of new questions and technology's seemingly unstoppable advancements. This development has in turn caused significant changes in a physicists expected tasks in his or her working life, be it either research or industry. As a consequence, computational perspectives have become essential parts in several of the University of Oslo's natural science studies, including the Physics, Astronomy and Meteorology branch, which is the subject of my study. These students will in their first semester at the University gain important insight in analytical and numerical mathematics, as well as the programming language Python. The knowledge and skills they build up during this semester is fundamental for working with courses further up in the system. For the physics students in particular, the first semester will lay the foundation for modeling physical systems and phenomena with computational perspectives in their second semester and their first course in physics: mechanics. Computational perspectives are integral parts of this course and stands side by side with traditional physics theory. To accomplish this, new course materials have been developed (including textbook material and exercises) which incorporates these new aspects as a natural part of the curriculum.

II. SOLVING ODE'S WITH EULER'S METHOD – AN EXAMPLE WITH NEWTON'S 2. LAW

Give a general example of what the students are doing. Or a specific example? Or no example at all? This section might very well be unnecessary.

III. THEORETICAL FRAMEWORK

A. The sociocultural theory of learning

And now, to fill this section with some text: The sociocultural theory of learning emphasize that knowledge is constructed through social interaction and in a specific context, not primarily through individual processes.[1] Lev Vygotsky, viewed as the founder of sociocultural theory, made a clear distinction between two forms of concepts one will learn and develop in life: spontaneous and scientific.[2] Spontaneous concepts are characterized by having grounds in everyday experience and being unsystematic and strongly bound to context. Scientific concepts, on the other hand, are decontextualized and organized in a logic and hierarchic fashion. The latter are also called "academic concepts", i.e. concepts found in any school setting. Even though spontaneous and scientific concepts are fundamentally different in the way we encounter and learn them, they are closely related to each other in the process of cognitive development: Spontaneous concepts have a development direction "upward" towards greater abstractness and, at the same time, they arrange for establishing scientific concepts in their "downward" development toward greater concreteness. [Check english reference: Vygotsky "Thought and language", this might be plagiarism].

When we now turn to Mikhail Bakhtin, the keyword is dialogue. ...

The purpose of this section: Lay the foundation for learning physics being about making meaning of the scientific story of physics and being able to speak its social language. Also declaring the view on imitation to be something fruitful for the learning process – a sign that learning is taking place.

Something about Vygotsky[1–4], Bakhtin[1,5] and references to Mortimer & Scott[6] (and relevant papers, perhaps Driver[7], Kubli[8] and Wells[9]).

B. Developing a conceptual understanding of physics

To discuss the development of a "conceptual understanding", we first have to clarify what that means. A well known phenomenon is students' ableness to solve assignments and doing well in tests without being able to show the correct understanding of the physics theory. This phenomenon, labeled as misconceptions, is the results of students' having an individual understanding of the physics theory and/or having memorized methods for solving the problem at hand.

Summarized in short terms: Using the language to express an understanding; to talk like a physicist is to think like one.

Relevant physics didactics research (Angell[10], Hestenes[11,12], Gautreau & Novemsky[13], Mazur[14], Novak et. al.[15], Muller et. al.[16], etc.).

C. Traditional and computational modeling of physics

Something about traditional versus computational modeling of physics. About awareness on different representations, model fitting behavior, algorithmic thinking (creating a plan) and scientific thinking. Relevant people: Angell[17], Gilbert[18], Sins[19], Oliphant[20], Yasar[21]? Futschek[22] and Landau[23].

IV. METHODS

Questions regarding learning and meaning making of physics require methodological aid from the social sciences. This study revolves heavily around qualitative observations [do I need the other two?] of two pairs of students solving compulsory assignments in mechanics. Three assignments with a considerable degree of computational perspectives were chosen to give grounds for the observations. Also: Make sure to point out that all transcribed discussion in this paper have been translated from norwegian – and double check with a fair amount of people that the translations transfer the same meaning.

V. RESULTS AND DISCUSSION

A. Working in modes: On knowledge being bound to context

As the heading says: Something that illustrates the students "working modes" related to Vygotsky's spontaneous concepts' strong relation to their learnt context.

One of the first observations made, was the students' tendency to find themselves in "working modes". Depending on the exercise at hand, the students' work tended towards either conceptual knowledge of physics and everyday experience ("physics mode"), mathematical relations and arithmetic calculations ("math mode") or sheer programming techniques or the programming language's syntax ("programming mode"). The physics mode and math mode has been documented by others,[17] and were essentially the source of inspiration for trying to document these modes again. The "programming mode", however, is a result of the new computational perspectives introduced in the mechanics course and consequently a brand new mode. As well as the characterizations mentioned above, the programming mode have some other features as well. When programming, the students' work has very little structure and they seem to enter some sort of "trial and error"-mentality for handling even the most basic problems, be it either mathematical, physical or computer based (i.e. programming techniques or language syntax) in nature.

First, I'll illustrate the physics mode. The two boys are about to draw a free-body diagram of a sprinter running a 100-meter sprint:

The physics mode:

G1 Should we not just – isn't a free-body diagram just – like this?
G2 Yes, but look – at the start, he'll have a kind of log [starting blocks] to lean against and ...
G1 Nobody has said that.

G1 is correct. Nobody has said that; the model has no such condition (yet). Even so, G2's initial thoughts are set on the real race – his first analysis of the race is based on spontaneous concepts originating from everyday experience (e.g. running for himself, watching sprints on the television, etc.).

Second, a bit later in the same assignment, the boys are reluctant to seek aid from course material and want to solve the exercise "Write a program to determine the motion of the runner from start to the finishing line" on their own:

The math mode:

G2 No, but we have ... We have an expression for the double derivative with the first derivative. And then we have the position as well – we have x – hmm. We have, like, no ... It's been a long time since I've done this.
G1 But ...
G2 Like, we have a system of differential equations $x_1' = x_2$.
G1 M-hmm?
G2 So we'll get out values for x_1' and x_2' – or the velocity, that is.
G1 What's that?
G2 If we solve this, we'll get values for a and values for v. And we can use Euler's, can't we?
G1 Yeah, we can just use Euler to solve those two and you'll integrate that, then – what'll you get – then you'll get your velocity?

[... some time is being spent on looking through the course material by my suggestion, but G1 won't settle with such an easy solution ...]

G1 No, I don't understand why this should be so difficult. Isn't this just a completely standard Euler? Where we can choose a standard Euler and we have a function $f(v,t)$? Which gives a ...
G2 Yes, wait a minute!
G1 Then we'll get, like ...
G2 A standard Euler? $x_{i+1} =$ ... or should we look at the speed as well?
G1 $v_{i+1} = a_i dt$ where a_i is always [... reads the expression for the acceleration ...] and we've got v_0. There's nothing stopping us?

The recalling of different fragments from the previous semester's course in numerical mathematics, gives this discussion a clear math mode-characteristic. In stead of talking about velocities and accelerations, G2 tends to call them "x_1' and x_2'", and instead of saying "$a(v,t)$", G1 uses the more mathematical "$f(v,t)$". Nevertheless, in the end they're able to bring their discussion over into a physics context. The fundamental mathematics, however, is being recalled from a distinct mathematical context; originally the students find themselves in math mode.

Finally, we take a look at the programming mode. As a first example, the two girls are working with modeling a 100-meter sprint. They have ended up with different values for the starting acceleration and have already spent some time going over J2's program code looking for typical syntax errors. They now discuss, rather shallow, while sitting in front of their respective computers which value of the starting acceleration seems most plausible:

The acceleration of a 100-meter sprint. A starting acceleration of either 5,5 m/s^2 or:

J2 I think it's a bit hard to say if it's reasonable, that he can have 11 $\mathrm{m/s^2}$ in the beginning as acceleration! Well, that's absurdly high!
J1 No, well, I don't think it's reasonable!
J2 No, but I just ponder on it falling so fast.
J1 Yeah, but well ... Either it's something wrong with my program, or it's something wrong with your program, 'cause we should have the same. And I regard my acceleration as more plausible than yours! *Laughs*

J1 opts for comparing the codes one more time. She also somewhat sets the mode to trial-and-error by means of comparison.

Another example takes place in the girls' third assignment. They have been given a working program code, with the exceptions of some values which have to be filled in. In this code, the angular acceleration of a periodically driven pendulum is being integrated by Euler-Cromers method to form positions to be plotted. The angular momentum itself is not being stored in an array, something both girls have believed to this point that it has to. If not stored in an array, it would be constant, they seem to think:

I Do you need an array for alpha?
J2 Yes.
J1 Hmmm ...
I Why is that?
J1 You probably don't need to store it all the time, but ... It's not constant. I think. I don't know. We can try something clever, we can try writing it like this, then we can see if it behaves like it's constant.

[...]

J2 But in the way he has written it, it looks like alpha is a constant.

[...]

J1 Like he has written the program? Yeah.
I Why is that?
J2 He hasn't written any index, "holdt jeg på å si"? [in english?]
J1 Because he hasn't given any alpha_0 and no array for alpha or anything. But it could be something we should find out by ourselves.
I But the way you have written alpha right there. If you don't store it as an array, would it still be constant for every loop?
J1 Since you're asking, it probably won't! But I think it should be!
I Yes, I'm probably giving some hints right now.
J1 Oh no, yeah, so you'll just update it every time – yes, that's clever!

In this case: also more capable peer (myself) and polyphony. Lastly, the boys are writing a program for the elastic pendulum:

G1 Do you make unit vectors, or what?
G2 Hmm?
G1 [Makes a decision without getting a response:] No, I'll just make these vectors and hope that Python is able to multiply them on its own.

He tries and hopes for no errors.

G1 I feel like this is kind of sketchy. From my part.
G2 Yeah, I too feel it being kind of sketchy, because – that r – that's ...
G1 Yes, I have to make an r_0 and a v_0, thank you.
I What is it that's being sketchy at the moment?
G1 No, I just ... I'm not entirely certain of what I'm doing. So I'll rather just gradually see if I'm doing something wrong.

Lack of structure, trial and error – in need of some sort of plan.

B. Starting to program without having a plan

As a follow-up to previous section's last discussion and programming mode's general lack of structure: The students do not have a plan for their programming. They read "write a program ..." and do exactly that.

The students never opt for analyzing given problems or specifying them precisely. In other words, they never "plan their modeling". Below, the one exception is illustrated with the initial discussion where G2 makes an attempt to create a plan, but encounters heavy resistance:

G1 But, are we still supposed to do this analytically?
G2 Nope!
G1 No, that's what I was about to say. I propose that we rather ... [rolls towards the computers] Well, he haven't said anything about it, so we may do this however we want to?
G2 The m was ...? Eighty. Then we should solve the system? [continues with pen and paper]
G1 Yeah, but it doesn't say that we're supposed to do this analytically?
G2 "Write a program to determine the motion".
G1 Yes, we can use the program to find the v for us.
G2 We still have to find out which equations we should put into the program. He doesn't ask about the acceleration.
G1 No, but we'll integrate with the computer?
G2 Yes! But first we have to ... We've got an expression for the acceleration dependent of the velocity. And then we're supposed to find the position, that is x, so we have to integrate a two times, right? It's dependent of the derivative of ... So it won't be an easy integral, in other words. I'm unable to explain it, but ...
G1 No, I understand what you're saying, but ...

C. The length of the discrete steps and working with black boxes

Also as a follow-up on the programming mode's lack of structure and trial and error-mentality: The step length being regarded as static and set "at random". Also: Something on some of the students' model fitting behavior and black box thinking.

The students never discuss the value of the step length. The few times it gets mentioned, a discussion never gets started. Instead, it generally gets its "usual value" of 0,1. In the following example, the boys are getting rubbish plots of an elastic pendulum motion and in their strive for solving this problem, G1 illustrates his view on the step length, dt:

G1 That r of mine is alarmingly similar to itself, "holdt jeg på å si". Okay. There's something wrong with ... Ah, no wonder, "$v + dt \cdot a$", my a must be erroneous.
[...]
G2 Well, I think it's as early as my acceleration.
G1 Hahah, that's what I'm thinking as well. Ah, this is weird. When I print out r_0 times – this is r_0 – and then I multiply it with dt, I get zero!
[...]
G1 So v_1 is correct. And r_1 is given by r_0, which is correct, plus the velocity v_1, which is correct, times dt.

In the last sentence, G1 implies that everything is correct except the step length, dt. Even so, he is unable to call attention to it. It's being viewed more or less as static. He is showing good insight into Euler's method, but is still unable to solve the problem. However, the possible problems caused by a step length being too large aren't unknown to the students. When the girls encounter a similar problem and eventually are able to solve it, J2 utters in frustration:

J2 He could perhaps have given a small tip that we should make a fair amount of steps? So that people don't sit around and ...
J1 No no no, they have taught us about this with Foreward-Euler for a long time – this we should know!

J1 is correct. They should know about this. And they probably do. They are just not aware ...

D. Selecting the tools for solving the problem at hand

On selecting the adequate tools. Not obvious for the students! Too many balls in the air (juggling with knowledge). Have a good look at figure 1 ...

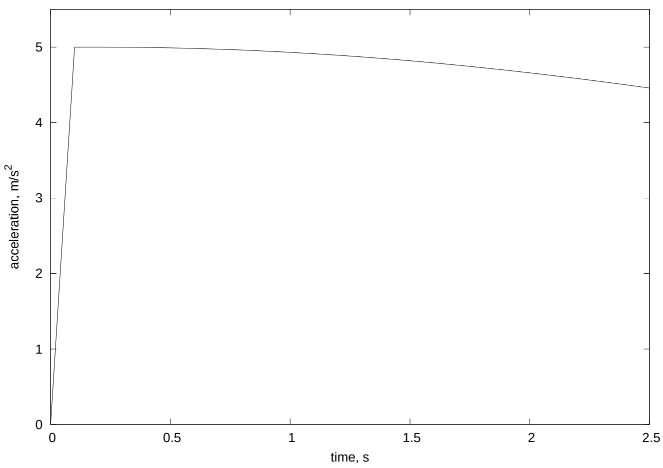

Figure 1: An erroneous beginning of the sprinters acceleration due to discretization and a faulty line of code.

J1 Do you get a somewhat weird beginning on the acceleration as well?
J2 I don't know, I've messed things up a bit here right now, so ... On the acceleration? I don't know!
I What's a "weird beginning"?
J2 A smooth start, perhaps?
J1 No, 'cause the acceleration starts at zero, but gets going very fast, so it becomes, like, straight up and such. And that's all natural compared to how he runs, but it just looked a bit weird. You will use a fraction of a second to get the acceleration from zero and up.
J2 Yes?

J1 Yes, so it's all right.
[...]
J2 I haven't gotten that, but ...
J1 That's why I'm asking, 'cause you haven't gotten that, but I have.
J2 But it's very logical, isn't it?
J1 I have no problem with it being like that. But I have in a sense no problem with it not being like that for you either, so I got a little – "what"?

When looking at the figure, there should ring a bell in the students' heads: "Discretization"! No bell is ringing! Note to self: There is a thin line between model and reality in this example as well, since it's "natural" that the sprinter needs a fraction of a second to gain his acceleration. Perhaps the heading for this section should be merged with the next one?

E. Model ... or reality?

About the students' being able to "model" without discussing or showing modeling insight. They should be discussing the model and the modeling with their respective restraints on nature, or "reality", when they instead discuss the *real* physical system. When "comment on the results" enter the picture, the students leave programming mode in favor of physics mode and starts discussing the physical system in an inadequate fashion. [They need to be pointed to how and what to comment!] Talking about physical systems is context bound to high school physics, where numerical mathematics and programming were out of the picture.

Alright, over to the boys:

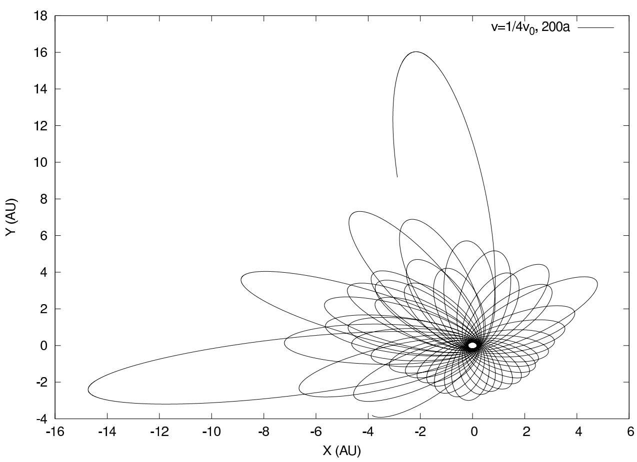

Figure 2: The revolvement of Jupiter around the Sun at one fourth starting velocity ...?

The boys' discussion of a plot like the one in figure 2:
I Do one fourth, like you did. [referring to G1's earlier attempt at one fourth starting velocity]
G2 Nooooo, ok. Aiaiai!
I What happens here?
G2 Nah, it's hard to say. It gets sucked – it starts there anyhow – then it gets sucked in, and then it gets more and more energy?
G1 Hmm? It can't get more and more energy?
G2 But it bounces out to here!
G1 Yeah, but at that point it's probably got zero velocity.
G2 Ah, right, I thought about it completely wrong. I'm tired today.
G1 'Cause it aaaalmost hits the Sun. Sweeps past the Sun. Or does it go through? No, it can't do that.
G2 The program would have stopped.
G1 Weeeell, would it?
[...]
G2 No, I'm out of ideas.
G1 No, but what happens, there aren't really any errors happening here, is it? It's just that it's being sent abruptly out again after sweeping past the Sun? The Sun bends its path tremendously.

F. Meaning making – the importance of dialogue and polyphony

The need for real dialogue with several hypotheses and points of view for understanding and meaning making.

VI. CONCLUSION AND IMPLICATIONS

A. The fragmentation of knowledge: On working in modes and being bound to context

Different exercises opt for different set of skills. These skills are learnt in different sets of context, in which "comment on the results" might be bound to high school physics, while knowledge in programming and discrete mathematics – which are necessary for discussing the model and modeling in detail – are bound to the first semester at the University.

B. The lack of awareness: Modeling with brand new set of tools

On the different tool sets and creating an awareness on how to use them, as well as creating an awareness on the differences between model and reality (and the limitations computer based modeling causes, e.g. discrete models). The new set of tools (programming and numerical mathematics) needs to get actualized in a physics context.

C. Developing modeling skills by imitating "the skilled modeler"

On Vygotsky's view on imitation and how the students should somehow be able to imitate "the skilled modeler".

D. Building up "the scientific story" fragment by fragment

On narrating (or ... *telling*) the scientific story. Dialogue and room for alternative hypotheses and multiple points of view. Theory fragments needs to be elaborated and connected to each other for developing "deeper insight". Understanding why one thing is erroneous, contributes to understanding why the other is correct.

E. The exercise text as narrator

I propose that the exercise text can be both a good narrator of the scientific story and the grounds for imitating good modeling skills. It demands, however, a certain amount of awareness concerning aspects of learning when constructing the text. The text should be both instructing as well as elaborating. It can help the students grasp the scientific story, rather than testing if they are able to narrate it on their own given the right amount of story fragments.

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