Modification of the Concept "Change" as a Result of Working with System Dynamics Model in an Educational Setting

by

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Abstract

This article concerns the problems that junior college students encounter when trying to understand and utilize the concept and insights traditionally provided by the teaching of mathematics. In this context, the concept "change" is significant because it is closely associated with the "derivative" and the "integral" as defined in mathematical analysis.

Our hypothesis is that system dynamics contributes constructively to the formation of the "change"-concept, essential to mathematical analysis. In the study reported i this paper, we investigate how high school students develop their understanding and use of the concept "change" as a result of a course in system dynamics that includes a total of 30 hours of lecture an assignments.

Background

The concept of change is not always seen as a central in teaching today. It is relatively rare that change, the causes of change or the consequences of change are central objects of teaching concern in the compulsory comprehensive and high schools. One of the reasons for this is that "normal" treatments of the concept of change and phenomena which undergo change, subject the development of an understanding of change to a mathematical formalism which constructs obstacles for the learner rather than providing learning support. We use mathematical tools such as derivatives, integrals and differential equations to understand change and these are abstract concepts, an adequate grasp of which necessitates an extensive mathematical or scientific education background. In passing; but not so as this will detract from the importance of this problem; it can also be pointed out that the 15-20% of high school pupils who meet this kind of mathematics do so "manipulatively". Arguably because of a lack of time, this kind of mathematics is rarely applied on the "real" world by them. As a result, they are given little chance to appreciate that integrals, derivatives and differential equations are in reality tools which they can use to develop models of the world, and to develop their understanding of change, the causes of change and the effects of change on different phenomena.

Another reason why change is given a rather neglectful treatment in school is that the concept is for the most part locked in with concepts of time, and time is a very problematic concept. For instance, it is relatively rare that when dealing with time we look at problems concerning decisions in previous time, and the consequences these decisions may have for change in present time. When, in school, do we discuss todays decisions and how these may change tomorrows possibilities? Time is only an object of concern in school in physics teaching, and only then in relation to motion.

My hypothesis is that by allowing high school pupils to work in system dynamics, and therein to treat change as as "flow" in a system dynamic perspective, possibilities will be generated for the school to aid pupils come to see the complexity of biological and artificial environments, without demanding a capability in highly specialized and abstract mathematics from them first. At the same time however, this environment will also offer inroads toward the kind of conceptual development which is fundamental for a deep understanding of derivative-integral concepts as well. The approach creates an educational environment which can and should form a bridging ground between formal mathematics and the real world. My belief is that by allowing pupils and students to work with system dynamics; and computer programmes which support system dynamics ways of thinking; new groups of pupils may be given insight into areas of the curriculum which previously realistically lay well beyond their capabilities, at the same time as pupils who work with advanced mathematical concepts will become able to make good these from new perspectives.

Two studies form the basis for the above assumptions. The first was carried out during 1989 and 1990 at a compulsory comprehensive school in Kristinehamn, Sweden (Introducing System Dynamics in Schools - The Nordic Experience, Davidsen, Bjurklo and Wikström, 1990). A second investigation was carried out in a Swedish high school between 1991 and 1992 and forms the background for this paper.

The investigation

The investigation is built on an interview study carried out with 13 high school pupils who were engaged with their second years studies on the mathematics and science programme. Two interviews were to be conducted with each pupil, who should have been involved in 30 teaching periods of system dynamics between the two interviews. Report writing formed a significant part of this teaching and teaching effects were targeted in the interviews. The interviews were carried out in December 1990 and April 1991. However, pupils in the Swedish upper-secondary school are not just involved in studying and being in school regularly. Their studies are often interrupted by trips and other activities and because of this some difficulties were encountered in holding the above group together for a period of five months. Because of this only 8 pupils were able to be interviewed twice. Two pupils only took part in the first interview and three in the second. The aims of the interviews were to identify the pupils conceptions of the concept of change and how this was developed or influenced by working with system dynamics.

The teaching which was given to pupils between the two interviews was aimed at providing them with the opportunity to develop concepts in relation to change in the world. The pupils worked with developing and examining models which drew them toward a process thinking. The teaching took up issues which aimed at developing the pupils understanding of complex relations within artificial and biological environments. Pupils were given the possibility to acquire knowledge which could change their attitudes and values regarding the complexity of interactions between technological, biological, economic and social environments.

The teaching encompassed problems which dealt with exponential growth where pupils worked with capital-interest, population growth, algae growth and so on. The pupils were given the opportunity to build and examine dynamic models which demonstrate both stable and unstable equilibria. These models were then coupled to understandings of the system behaviours which explain extinction in biological communities.

Fluctuation dynamics formed an important part of the teaching. Here pupils worked with second order systems and looked at the qualities which characterize fluctuating systems. A great deal of emphasis was placed on setting pupils in a situation where they could identify that signals into a system could give unexpected return signals from the system after a time period greater than that at which the signal in was anticipated to act on the system by them. The pupils also met higher order systems simulated by models developed to account for contagion within a given population. Models simulating the spread of toxins within a food chain were also used as examples of higher order models and so as to convey the "accumulation" of poisons within such a chain. As a general, but not always clearly articulated aim, it was hoped that pupils would gain insight into non-linearity and positive and negative feed-back.

Evaluation

My belief is that the interviewers relation to the interviewee and knowledge of the field in question has great influence on the character of the information which can be extracted from an interview. As I was one of the examining teachers as well as researcher in my study I was clearly unsuitable as interviewer. The question actualized though was to what degree the interviewer needed expertize in mathematical analysis or to what degree he or she needed expertize in posing questions in an education research context. I chose the second line. The interviewer must pose certain demands on the quality of reasoning and explanation given in an interview. The respondent (in this case the pupil) has to form his or her answers in common parlance which the interviewer can understand. The respondent cannot hide behind mathematical explanations in the acceptance that these are generally accepted in the mathematics community the interviewer shares them. The respondent is forced to reword his or her explanations. These may not contain mathematical terms of reference, but should explain such in common terms. The interviewer can say, without fear of stretching the truth, i don't know what derivatives are, you will have to explain them to me, thereby forcing the respondent to express him or herself in common parlance in relation to mathematical concepts: with this quite possibly being a new experience for him or her.

My assumptions about the influence on the character of interview transcripts of the relationships between interviewer and interviewee and the inter-viewers (lack of) familiarity with the field of knowledge had substance, however, some unforeseen drawbacks have ensued also. The interviewer, because of his relative lack of knowledge of the field compared to the respondents, has at times missed some interesting twists to discussions which have been developed by them. The interviewer has missed taking up some interesting angles and encouraging respondents to develop lines of thought, has missed out on asking further questions, by virtue of his not being able to appreciate the relevance of some of the respondents statements. In other circumstances the interviewer has even interrupted the respondents at critical times during their development of an argument for the same kinds of reasons. A further point to note is that the interviewer learns about the field in question as the interview series progresses and the character of the interviews has been different across the series because of this. An example of this latter point can be provided by recourse to the concepts of stable and unstable equilibrium. The interviewers natural curiosity about this concept was obviously curbed across the interview series, to be replaced by a more formal search for the respondents specific understanding of the concepts. In general terms the above drawbacks are relatively small when compared to the advantages which are gained by engaging the respondents in "common" speech, where he or she is forced to explain concepts in other terms than those which they were initially presented to them in.

Results

When the interviewer and the respondent (the pupil -P) discussed the concept of change in the first interview; ie. the interview prior to teaching in system dynamics; some pupils had substantial difficulty in expressing themselves clearly in relation to this concept. When the interviewer tried to discuss the causes and consequences of change communication became quite difficult. Some pupils could discuss things which had changed and they could give examples, but they found it difficult to speak in relation to causes and had problems talking about phenomena which were influenced by change.

Some pupils had a more or less well developed consciousness about the chain of events cause - change - phenomena. They could discuss ageing, learning, warming, recession, the ozone layer, quality of life, hunger, eating, tiredness, sleep, the population dynamics of a flock of Canada Geese, and so on.

One group of pupils were very clear about there always being an event which preceded change and an event which always followed on from it. In these terms, change was always seen as preceded by cause and followed by a change in behaviour in the objects or phenomena which had been exposed to change. In this context the pupils also showed that they saw time as involved in an interplay between a number of different variables:

> People change don't they? You can learn, gain in experience.
> *What causes change?*
> Curiosity perhaps.

In this text extract all three components (change, phenomenon and cause) are present. The **change** is learning something. The **phenomenon** influenced is that of experience. The **cause** is curiosity:

> There's just more and more computers.
> We have a need of them as we are so dependent on time.
> *Demand for what?*
> Everything, I don't really no what to say, it all depends which time we're in. It maybe TV, computers, parabolas. Demand forces forward the product. The cause of it all is human greed. Only nature can say stop.

Here we find the same fundamental concepts. The change is in demand. The cause is greed. The phenomenon production. However, with further consideration of the above argument we could view the pupils comments at a slightly different level. Demand could be seen as cause, production as change, and differentiation in technical goods as phenomenon.

In all the first interviews the interviewer tried to discuss with respondents how a cup of initially warm coffee changes temperature. Sometimes the result can be: "that's too difficult, I really don't know". At other times answers can be quite comprehensive:

> It evaporates, steam comes off and so the coffee loses water. It is of course warm when you loose water. The water in the cup disappears. The larger the area the more evaporation. As time passes the temperature falls and there is less evaporation.
> *What does the temperature change depend on then?*
> Time and how cold it is in the room.

Again we can see cause, phenomenon and change. The cause is the temperature of the water and the surface area from which evaporation takes place, change corresponds to the change in volume as steam (water) leaves the cup and the phenomenon is that the water level reduction itself.

A pupil who lives on an isolated farm surrounded by it's own small estate is able to hunt on those grounds quite freely. He has drawn up issues connected to hunting in both the interviews. In the first interview he took up problems with Canada Geese.

> In the autumn the Canada Geese come down from the Vänern region. It would be better if more people hunted these geese as the flock grows too much otherwise.
> *Why are there so many geese?*
> It has to do with it's lack of natural predators. Eagles may take a couple but once they get full-grown there are few animals that can take them down. Then they also have a lot of young. Up to ten roughly of which six might survive. That's too many you see and the force out other types of bird. At least that's what I think.
> *Is this population growth likely to continue unabated?*
> Yes I reckon so, at least unless hunters get a better chance to pop a few. And they're difficult to hunt too, always on their guard.

The above description is of a kind of dynamic model. The pupil has knowledge about some of the causes of change, for instance a large birthrate, lack of predators and the difficulties of hunting brought about by the alertness of Canada Geese. Change is population growth and the phenomenon is the amount of gees which effects the existence of other species.

When the interviewer posed questions about hunger the pupils showed a fairly consistent kind of reaction. This isn't perhaps surprising in that they all have some 17 years of experience of this phenomenon. It is still of interest however to examine their response:

> The more I eat the more more hunger is abated and finally it goes away.
>
> "If you get only a little food then you will be hungry. The more food you get the less hungry you feel. Here you have so much food that hunger is more or less equal to zero."
>
> The change, the disappearance of hunger, that is that when you are hungry you need energy so that you can live and so you eat. You take up energy through food.
> *Can you measure this kind of change?*
> I don't think so.
>
> *What is hunger caused by?*
> You haven't eaten.
> *How can you effect hunger?*
> By eating
> *What happens to hunger when you eat?*
> It is reduced.
> *Hmm. What happens to hunger when you exercise?*
> Yeah, nothing.
> *Yeah, is there anything other than eating which effects hunger?*
> If I sat and watched you eat now and my stomach was empty I would quite probably become hungry.

Drawing in reasoning about hunger in this way can seem trivial and quite meaningless, however, I feel it is important to show that the concepts of cause, change, phenomenon and feedback to the system are held by the pupils in the investigation. These concepts and their relations are fundamental for understanding the patterns of behaviour exhibited in our surroundings.

Almost all pupils in the first interview demonstrate that they have the necessary concepts needed in order to deal adequately with the concept of change. Their lines of reasoning are more or less clear depending on which field is being dealt with, but particularly food, eating and hunger are discussed freely by them; if with a touch of irony. Note the negative feedback in the sequence:

How can we influence hunger?
By eating.
What happens to hunger when we eat?
It is reduced.

Cause -> Hunger
Change -> Eating, change in satiation, changes in energy reserves
Phenomenon -> Satiation, energy reserve

A further observation which can be made from the first interviews is that the pupils have a fairly consistent model of thought containing the components cause, phenomenon and change but that the model itself is part of day to day communication and is therefore not a conscious model. Their problems become more obvious when they are pressured to quantify change. Here are some examples. The first has to do with the coffee cooling example.

It cools more or less at a constant rate or maybe just bends off a bit toward the end.
You mean it doesn't go as quickly at the end?
Yeah, as it reaches room temperature.
Why shouldn't it go as quickly then?
I don't know.

The pupils tries to construct an aim oriented behaviour for the object in question, but lacks the tools for constructing such.

Changes in demand over time, is there any way of measuring this?
I reckon that would be an easier kind of change to measure.
How would one measure it?
I would think you could start just statistically on a goods from production start to end of line. To start with they have like "golden years", or whatever it's called, and then, if we take TV, first everyone wants one then after a few years everyone's got one.

When the interviewer asks the pupils how to measure change it would seem that about half of the time the pupils do not seem to have any clear idea about how they could go about this. Quite simply, most of the time they don't seem to feel that change can be measured. The pupils who do set about trying to describe how to measure change start from the manipulative methods they have learned from mathematics. The behaviour of a phenomenon is described by using a curve. From the slope of a curve, change, or as the pupils put it the derivative, can be ascertained. The pupils describe two ways in which the slope of a curve can be fixed. They take a distance in the y-direction and the equivalent distance from from the x-direction and divide one by the other or they start from a point on the curve and allow this point to move towards a second point. A line drawn from the first point to the second is taken to represent the slope of the curve and thereby change or the derivative. The size of change is in other words taken to be a particular characteristic of a point on a curve.

Another situation which illustrates the pupils ways of thinking appears when they are asked to describe the relationship between hunger and eating. The pupils describe a static table or a curve which shows this relationship. We can see that the pupils do not see changes in feelings of hunger as something which is connected to both time and eating.

When pupils are asked to quantify change their lines of reasoning become static and "state" focussed. When they discuss the growth of experience they don't affix a time dimension to this but rather attach their explanation to an accumulation of experiences which can be totaled up.Time is rarely discussed by pupils at all in this context. Rather than seeing change as coupled to time they see a static relationship which can be expressed in a curve. Most characteristic of all however, is a view of change as "passive". Something which is decided over by events. When coffee cools for instance, this is because the coffee has a higher temperature than the surrounding room. Changes in temperature are found by measuring the temperature after certain time intervals and dividing the fall in temperature by the amount of time which has passed. No pupils pointed out that the fall in temperature is due to energy leaving the system (the coffee and cup) because it is poorly insulated . Neither do they point out that if we insulated the cup effectively the fall in temperature could be slowed down considerably or even stopped. No pupils point out that there is a fall in the amount of energy in the cup and that it is this which brings about the change in temperature.

In the second interview, after the work in system dynamics had been carried out, the pupils showed a different kind of line of reasoning around the relations between phenomena and change. The pupils were able to clearly indicate that the behaviour of a phenomenon was steered by change, where change was seen as "everything that went in and everything that came out of a system". Time became something which formed a basis for their reasoning, but what is important is their way of viewing change. These developments became most clear when they were encouraged to quantify change. Here it became clear that their line of reasoning and perspective had shifted from being static where change was brought about by phenomena and can be described in relation to a point on a curve, to a dynamic point of view where change is dependent on time and influences the phenomenon. Change became the decisive element, to quote pupils, when something "grows, lives, dies out, spreads, fills out, empties" and so on.

Some of these pupils had failed in their mathematics lectures to capture an adequate understanding of derivatives, but despite this were able to explain how negative change could bring about a reduction and how a phenomenon behaved influenced by positive change. Pupils who had not mastered derivatives could, by recourse to everyday language, explain stable and unstable equilibrium despite this. They used the qualities of change in different situations and fields in order to do so. My feeling is that the pupils had begun to see change as subject and phenomenon as object. In the interviews there was even evidence that some pupils could "prolong" the argument and were able to see the cause of change behaviour. They could see how information was feedback from the phenomenon which had been exposed to change to the change itself, which thereby changed in dimension and once again began to influence the phenomenon. Insight about feedback effects in a system is made easier, if not enabled, by the insight that it is the phenomenon which is influenced by change and not the reverse.

The pupils initial conceptions of change; those which appeared in the first interview and prior to systems dynamics education; can be traced back to their traditional mathematics experiences, where in introducing the concept of change one starts by defining derivatives as elements which are manipulatively deduced from a function. In many instances the concept isn't given a chance to develop and mature further. When we begin to consider how pupils are encouraged or steered toward an understanding of derivative = change in mathematics education, we can begin to see how this kind of understanding runs against the behaviour change exhibits in the world. Reality does not butcher change into small parts in order then to analyze and find ways of describing it. In nature change in the behaviour of a phenomenon is added to continually over time and can be observed directly as in the spread of disease, radio-active fall out, the formation of political constellations, the accumulation of poisons in a water table, population growth, knowledge, capital, speed, position, energy and so on.

In order to exemplify the pupils lines of reasoning during the second interview I shall here present a few extracts from interview protocol:

What have you drawn there, it looks like a jar?
It looks like a jar yes, it is a jar. Interest flows into the jar and capital thereby accumulates in it. If this was to continue things would be pretty healthy after a few years, they are taxed as well and the amount of tax is decided from a taxation index geared to the size of accumulated capital.
What happens then?
It becomes constant after a while.
Why does it become constant?
Because the application of the taxation index means that tax is proportional to the size of the accumulated capital.
What happens if you take money out?
If you took a lot of money out the thing would collapse and there would be no money left in the jar.

Does this have anything to do with derivatives?
Yes same as everything else does.
Why?
I don't know.

This is time and this is money.
Does the interest just keep on growing then?
Yes it has to because there is more and more money to gain interest on, then there is taxation here, another flow.

What is a derivative? I've never read about them.
Seriously or do you just not get it.
Seriously, I've never read that kind of maths.

Here the pupil begins to explain for the interviewer how to do a derivation of a function with the form $y = x^2 + 2x$
This falls back onto the manipulative approach the pupil has learned in mathematics. Neither the pupil nor the interviewer understand what the pupil is try to show.

The interview shows that the pupil has difficulty combining the derivative concept from formal mathematics education with the flow and change concepts developed in systems dynamics. There is no link between the pupils mechanical derivation of a function and the correct description given of the behaviour of capital as a consequence of a flow (the derivatives) value. There are parallels though between the mechanical derivation of a function above, and the ways pupils tried to explain change as "the slope of a curve" in the first interview.

In the first interview pupils showed they knew the slope of a point in a curve described a change. Here the pupils make an association between the concepts derivative and change.

Indeed, they describe how a derivative is generated from the behaviour of a phenomenon. They redo this even in the second interview in connection to specifically the concept of derivative. They move their consciousness from function to change.

This is not so when pupils discuss change in relation to system dynamics. Rather there it is change which controls the behaviour of the phenomenon, and the pupil can even pursue a quantified line of reasoning about the qualities of change and how these effect the phenomenon.

In the first interview the pupils were able to see change and flow as influential on behaviour as long as everyday speech was used, but as soon as they were asked to quantify they switched to a line of reasoning in which they saw change as influenced by a phenomenon. This is very clear in the following extract from a first interview:

If we were to stop using freons altogether then what would happen with theses changes then?
It will stay the same as it is now a while because even if we do stop now it's not a total stop, there are still freons in the air and at refuse dumps and that.
How would you describe that sort of change if you were to quantify it?
It would be the same, a vertical line and a horizontal line and divide them.
What is the cause of change then?
The cause is that we let ozone escape into the atmosphere and it effects the ozone layer by changing ozone to ordinary oxygen so the ozone layer becomes damaged.

This is ta pupil who discusses equilibrium:

But it evens itself out so that it stays at a certain level and there is a balance between nativity and mortality rates. It can also fall, it depends on how many take part in the hunt.
What happens then?
Well, then they shoot them all, a lot more than have been born, or if they don't shoot ...if they notice that numbers have become low but go on shooting it can fall straight down anyway if there have become so few that there are fewer being born than dying.

And the curve, here's the derivative, the sum of births, deaths and from the hunt, that's the change. Here under the line we have a negative growth, numbers getting smaller, and above the positive where numbers increase, and here is a stable point.
Is the population zero there?
No, it means no population change. The change is zero. You have two points and in one of them the derivative is negative on one side and positive on the other so the population moves toward that point but in the other point it'll be positive in that direction and negative in the other so it moves from that point.

The above shows a line of thought which describes movement and is dynamic, but the interesting thing is that the pupil can give a correct explanation as to why the system has a stable and an unstable point. The line of reasoning is developed upon the pupils belief that the derivative is something which causes level changes. Compare this reasoning with the same pupils argument in the first interview:

What happens when you pour warm coffee into a cup?
It gets cold. We have time here and the coffee there.
If you were to measure that change how would you go about it?

You could take out the cooling curve coefficient here and measure the derivative. If you want to know exactly in one point you can take the tangent.
How do you do that? I don't know maths can you explain?
No, not very well anyway, but the maths teacher who's pretty good explained when we started with this.

Conclusions

Before working with system dynamics and simulations, the pupils lines of reasoning are static and condition oriented. Statements are not connected to time but to a string of experiences or events which are related to each-other in a static table. Time is rarely discussed, particularly in relation to change.

We find that pupils who have participated in the investigation have now developed an arsenal of tools with which to deal with and discuss cause, change and phenomena behaviour. They also have a logical "direction" in their lines of thought that change creates phenomenon behaviour rather than the reverse. Mathematics teaching does not help this logical directionality in thought to develop but rather opposes it. The influence of maths teaching has shown itself to be so powerful, that even when pupils have worked with system dynamics and can discuss quantitative aspects of change in terms of the influence of change on phenomenon behaviour, they slide back to their alternative model in "mathematics situations".

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