LEARNING PATHWAY AND KNOWLEDGE CONSTRUCTION

IN

ELECTRIC CIRCUITS

by

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1. Introduction

In 1991 an international workshop on "research in physics learning" was organized (Duit, Goldberg, Niedderer 1992). Its aim was "to promote a new orientation in research towards empirical investigations of students' learning processes" (Niedderer, Goldberg, Duit 1992, p.10). The idea was to proceed from the successful research tradition of investigating "alternative conceptions of students", mainly before teaching, towards an analysis of *cognitive processes during learning.*

The following study is based on a tutorial teaching process with three college students (age 21) [3] and one teacher over six sessions in electric circuits. The whole process was videotaped and afterwards transcribed. The analysis of learning processes was done with a qualitative interpretive approach. Its main results are to describe students' learning pathways from a prior conception to three new intermediate conceptions during the first two sessions and giving evidence to a hypothetical explanation of knowledge construction (Lijnse 1994) during a generative process (Wittrock 1994).

2. Theoretical framework

We earlier developed a rather general view of a cognitive system for analyzing physics learning (Niedderer, Schecker 1992). We again follow the same ideas with distinguishing stable cognitive elements in a "deep structure" from "current constructions" in the context of actual situations. But in the present study we use a more narrow view focusing mainly on cognitive elements like students' conceptions and language, related to research traditions in physics education (e.g. "cognitive structure and conceptual change", West, Pines 1985), not taking into account more general cognitive elements like metacognitive beliefs, general frames of thinking, and interests. The described cognitive elements and conceptions are constructions of the researcher; their internal validity is tested by their power to explain students' constructions as far as possible; their external validity hopefully will be determined by their usefulness for other researchers and for teachers.

2.1 Conceptions

We use conceptions as if they were representations in students' mind. However, we do *not* believe in general that students' minds are really working with these representations. Conceptions are characterizing those "current constructions" which are most likely to occur. We expect further research to discover more general production systems creating this kind of behavior and these constructions of meaning. Yet, to think of representations enables us to work on students' cognitive systems in a very content specific way: conceptions are seen as cognitive elements related to the special content domain.

We therefore describe conceptions as a set of propositions which would produce a similar behavior of students if represented in students' mind. Our description always starts with the main feature - the nucleus[4] or core idea. The conception is then further elaborated by smaller "pieces of knowledge" that students seem to be applying in problem situations. These pieces are called "facets" of the conception. Facets are sometimes best formulated as basic propositions, being the

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[3] Prospective elementary school teachers.

[4] We use the term nucleus in the same sense as Schwedes and Schmidt (1992, p.189) as a central idea which to some extend produces all the special features of the conception.

"imaginary rules" by which students conceptions can be characterized. [5] "Facets" are especially used to show differences between different intermediate conceptions and between intermediate and scientific conceptions.

Evidence for conceptions is always given in three ways: by analyzing the process of its developmental teaching and learning process, by looking for evidence of some subjective feeling of understanding of students and by giving evidence for some stability by showing the use of this conception in later situations.

2.2 Learning pathways

Learning pathways were introduced into the discussion about analyzing learning processes by Driver in 1991 (see Scott, Asoko, Driver 1992).[6] In this paper we describe learning pathways by describing a learning route starting with prior conceptions and coming to intermediate conceptions during teaching (see also diagram below in 2.3). Following our theoretical model of cognitive systems consisting of *current constructions* and a *deep structure* (Niedderer, Schecker 1992, p.84) we look for those cognitive elements belonging to the deep structure which have already developed some stability during the learning process. So, if new ideas are of some stability and influencing as such the further process of learning, we call them *intermediate conceptions.* A *learning pathway* can be described by giving evidence to those "metastable" intermediate conceptions as kind of stepping stones [7] of the learning process, and by describing when and how they have been developed [8]. As a research program, we start by analyzing prior conceptions, go on to identify intermediate conceptions, and finally analyze the process of knowledge construction as an interplay of previous cognitive elements and teaching inputs, describing conceptual development in relation to aims and content of instruction.

Students start their learning process with *prior conceptions* from their everyday life experiences (e.g. an everyday life view of "current"), which in the field of electric circuits are well known from previous research (Duit, Jung, Rhöneck 1985; Pfund, Duit 1994).

Intermediate conceptions (IC) are conceptions developed during the teaching-learning process, being different from prior conceptions and in most cases still different from scientific conceptions. They are "in between". They often combine ideas from everyday life with some scientific ideas, thus making sense of science.[9] Intermediate conceptions are new cognitive elements developed during teaching. This means they are somewhat fragile, not yet very stable, but sometimes being used spontaneously later-on. Nevertheless, they have already acquired some stability. Their status

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[5] If a computer model would follow these rules it might produce the same explanations, questions, answers, etc.

[6] Scott (1992, p. 203ff) discusses "pathways in learning science". From analyzing qualitative data with one student Sharon (audio taped group work, diagnostic test and student's own diary) he describes Sharon's ideas before and after teaching and the development of these ideas during teaching as a case study, relating these ideas to the structure of matter.

[7] Brown and Clement (1992, p.384-386) talk about "intermediate conceptions" and "intermediate concepts as stepping stones". Examples of those intermediate states are a "hold back tendency" and a "keeps going tendency" as different preliminary notions which in physics are generalized to the concept of inertia.

[8] Dykstra (1992) gives also an example of a learning process which he calls "a series of conceptual changes". Here he distinguishes an "initial conception", a "refined initial conception", a "first version Newtonian conception", and a "refined Newtonian conception". The second and third of these observed conceptions would be very much the same what we call intermediate states.

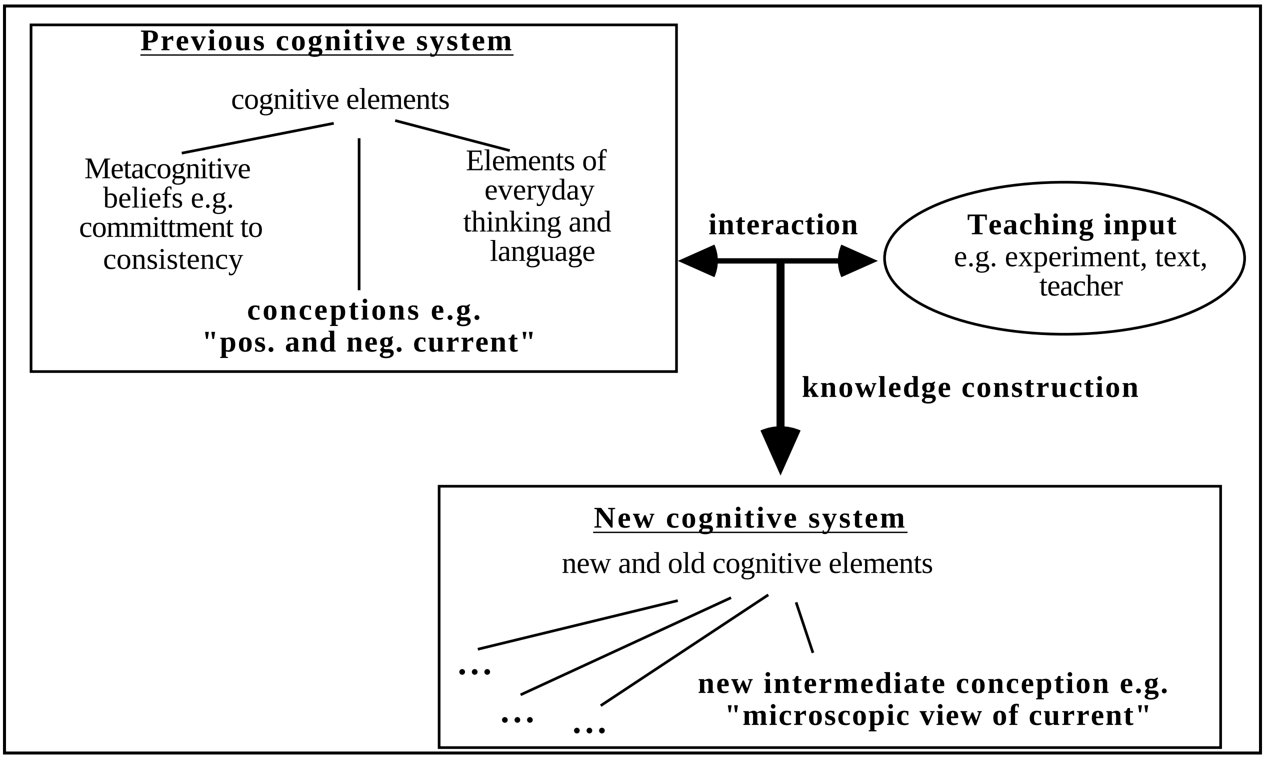
[9] Galili, Bendall, Goldberg (1993) also give examples of "hybrid knowledge" with "intermediate states of knowledge" in a learning process in optics. Especially they describe as one important intermediate state the "relevant ray diagram" which shows a different meaning for ray diagrams than in physics but, on the other hand, also shows some ability of students to use ray diagrams.

might get either higher or lower during the ongoing learning process.[10] Therefore, as an important methodological point, we only accept students' ideas as an intermediate conception if we can find evidence for some stability of these newly developed cognitive elements in students' thinking some time later, perhaps in a different context. They should be somewhat stable, e.g. more stable than spontaneous ideas only used once. Students' final state consists of several "layers" which also contain the intermediate conceptions.

Finally we take *scientific conceptions* (SC), held by the teacher (a physicist), as one reference point of analysis, which also describes the aim of teaching.

2.3 Knowledge construction

With the idea of *knowledge construction* [11] [12] we try to reconstruct students construction process during learning.



A new cognitive system is built or constructed from a previous cognitive system with elements such as conceptions, schema and everyday language, in interplay with new experiences (experiments) and the contents of instruction. During the teaching and learning process an interaction between prior cognitive elements (conceptions and others) and specific parts of the instructional setting occurs, producing new conceptions in students' minds (see graphical overview above). This interaction is perhaps mainly guided by some kind of cognitive resonance[13].

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[10] The conceptual change model as it is used by Hewson, Hewson (1992) distinguishes between new and existing conceptions. This relates to prior and intermediate conceptions. "A key factor in the learning process is the status ... that new and existing conceptions have for the learner".

[11] Lijnse (1994, p.7) lists "understanding knowledge construction" as a research category in science education.

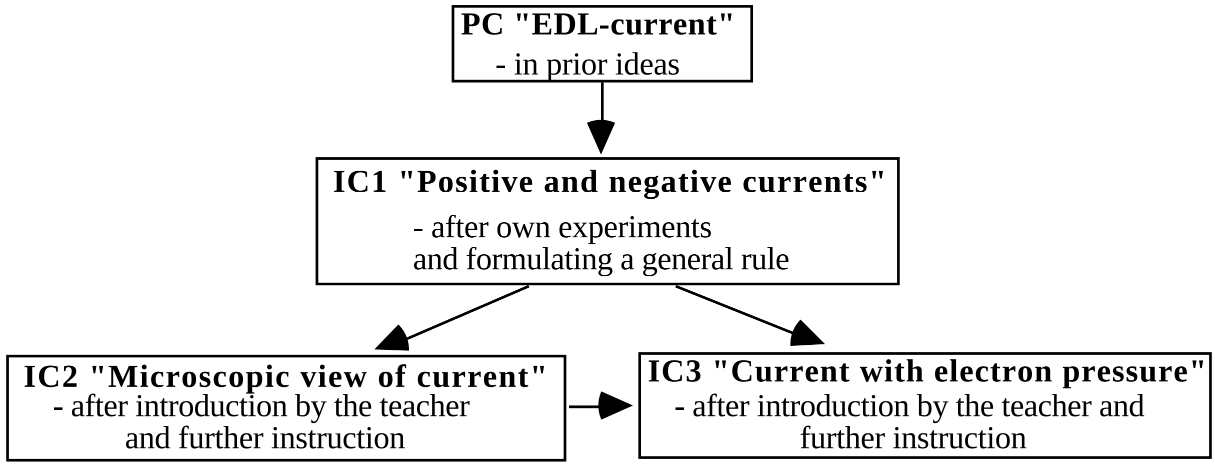
[12] Scott, Asoko and Driver (1992, p.321) talk about "the construction of scientific conceptions" not primarily from a cognitive perspective; they are more interested in teaching strategies.

[13] This idea of resonance was developed by Ernst von Glasersfeld during discussion at the Bremen workshop in 1991. He was comparing the teaching input to a pizzicato tone (with many frequencies) send to some room or cavity and the echo being determined by resonances.

3. Learning pathway and knowledge construction over two sessions

The following results could be seen as a story of a constructivist learning trial showing teachers intentions and teaching inputs on the one side and students' constructions and learning pathways out of that on the other. We mainly focus on one student's constructions (Lynn) and her intermediate conceptions but so far seeing no big differences between the three students. However, we see the emerging intermediate conceptions being different from teacher's intentions.

The following diagram gives an overview of the learning pathway, which is mainly started in session 1 but further developed especially with respect to "pressure" in session 2.



Learning pathway in sessions 1 and 2

3.1 Prior conception "EDL-Current" ("current 1")

Teaching input, intention, context provided

The teacher has the intention to teach in a constructivist way and starts with elicitation of students ideas in a questionnaire "Your Prior Ideas about Electricity". The key phrases "ideas about electricity", "what is moving in the wires", "one or more wires", "why you think the bulb will glow" and "arrows to show the direction" in the questionnaire are setting the **context** for students' answers. The word "current", though, is not used in the written text of the questionnaire.

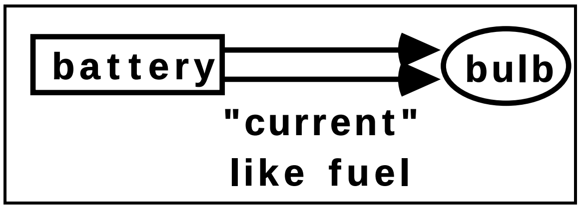
This already is an interesting example of a divergence between teachers intentions and what really happened in students' minds: The teacher had intended to elicit students' prior ideas as a starting point for **later** learning whereas in students' minds this questionnaire already started some construction processes, which afterwards affected their further cognitive activities in constructing their first intermediate conception.

General description of prior conception

We now describe the center (core, nucleus) of this prior conception [14]:

Prior conception "everyday life current" ("current 1"):

Current is seen as a substance containing energy like fuel, not transporting energy like water. Current(s) move(s) from the battery to the bulb in one direction thus bringing the energetic stuff to the bulb. So, movement is necessary but is not the essential feature of current; speed is not



[14] Which is well-known from previous research. Yet, this description of the nucleus differs from other descriptions, which put the current consumption idea in the first place.

relevant for the amount of current.

This conception can be more precisely characterized by facets, which are listed in appendix 1.

We omit the parts "evidence from selected dialogues" and "evidence for some stability and effects on later constructions" to shorten the presentation.

3.2 First intermediate conception "Positive and negative currents" ("current 2") [15]

Teaching input, intention, context provided

Knowledge construction of students often goes on in ways which are not intended by the teacher. The development of the first intermediate conception "positive and negative currents" is a good example. This intermediate conception was neither intended nor noticed by the teacher.

The intention of the teacher was to have students do preliminary hands-on experiments and thus gain some fundamental but very specific knowledge. His expectation was that the students would gather knowledge like: How battery and bulb should be connected and touched to work properly to light the bulb. In addition, he had the idea that the students' prior conceptions should be more elicited.

On the students' side something different happened. They had more problems than expected to find a circuit which makes the bulb light. In fact they took about 20 minutes to find that out! When they finally found out the solution this was a big success and meant a lot to them. From the many trials they tried and drew see how their brain was working intensively and constructing meaning of how a circuit works. This came together with two other preconditions: The teacher had given some preliminary experiments and explanations about positive and negative charges just before this unit was started. From the results in this study could be said that this knowledge was very effective in students' minds, it had a strong influence on their knowledge construction. After having this big success in their own experiments students were asked to formulate a general rule. This also turned out to be a successful task causing students to go on with their knowledge construction on a higher level with talking and writing. So they did a very good job bringing together all their new knowledge from experiments, their prior knowledge from previous teaching, their prior conception "everyday life current" and some special knowledge from everyday life.

The new experiences from experiments were: You need to have two different connecting points at the battery, two different connecting points at the bulb, and two different connections. This fits together with the idea that you need two different currents coming to the bulb and producing light there. The two currents were clearly to be a positive current and a negative current. So Lynn constructs her own theory which turns out to be what we call an intermediate conception . This is not realized by the teacher.

So the teacher had formed a good constructivist instructional frame by allowing students to do their own hands-on experiments and afterwards write down their own "general rule". The students were really making sense of their own by taking together the new experiences, the prior teaching about positive and negative charges, and their own notion of current bringing something energetic to the bulb. In this situation the teacher perhaps could have done better teaching by realizing these cognitive processes and intermediate conception as a result in students' minds and asking them to think of new experiments to test their theory.

He did not provide further opportunities to develop this intermediate conception, e.g. to frame new questions and to plan new experiments by their own. Instead he goes on with his plan starting to introduce pressure with some additional information about protons and electrons. [16]

[15] This conception is very similar to the well-known **"clashing currents"** model found by Shipstone 1985 and other researchers. In this study, however, it has a different meaning: students construct a special enriched version of this conception from their experimental results and talking and writing activities. It appears as an intermediate conception after some teaching, in a similar way as in the study of Schwedes/Schmidt 1992

General description of new intermediate conception

From interpreting the drawings and statements of Lynn shown above and some more statements given during discussions we come to the following general description of the core/nucleus of the newly developed intermediate conception:

Intermediate conception "positive and negative currents"("current 2")
Positive and negative charges come to the bulb, and by coming together produce light; this explains why you need two of each: separate connecting points at battery and bulb, two separate wires and how electricity is producing light [17]

This conception can be more precisely characterized by facets, which are listed in appendix 1.

Evidence for some stability

We see this intermediate conception of great influence on all later learning processes. It especially has a great impact on how the intermediate conception "pressure" is formed with special emphasis of negative means high pressure and positive means low.

Very strong evidence for Lynn having established this intermediate conception "positive and negative current" come from a dialogue some time later in session 1, when the teacher is introducing new ideas of electron movement explaining current.[18] Lynn about ten times is actively questioning this idea from the point of view of her first intermediate conception, thus contributing very much to the dialogue, but nothing to the new idea for at least ten minutes. This - together with other evidence from later sessions - shows some stability of this intermediate conception.

3.3 Second intermediate conception "microscopic view of current" ("current 3")

Teaching input, intention, context provided

The instruction which lead to this second intermediate conception was different from the previous section. Instead of giving open-ended tasks - which resulted in student's own knowledge construction - the teacher started to explain current in a more scientific way using a model of **electrons** moving (and protons staying) in the wires. He intended to introduce pressure and started with some information about protons and electrons and their motion, which in his mind had only the character of preparing a better introduction of the concept of "pressure" and "pressure difference". With this intention in mind he in fact gave a lot of verbal information about electrons and protons, about their movement, etc. The teacher again tried to establish a constructivist instructional frame, this time by guiding an open-ended discussion, with small bits of teacher information included. Doing this the teacher did not expect special resonance in students' mind.

Students seemed to like those ideas more than expected and constructed their own theory of electron motion during this teaching dialogue which turned out to be what we call an intermediate conception "microscopic view of current" ("current 3"). This was only partially realized by the teacher. Coming to this conception, again was not the aim of teaching!

The teacher sticks to the instructional plan to introduce pressure without a clear relation to a microscopic view. He does not provide further opportunities to develop this intermediate conception, e.g. to frame new questions and to plan new experiments by their own.

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16 We do not give any details of teaching and knowledge construction here, but they will be published soon.

17 In a more general - but important - sense this is even right from a physics point of view: light in any system of atoms, molecules or solids is produced by changing the configuration of negative charges in relation to the positive!

18 This dialogue is shown and interpreted in detail in the next section because it leads to a new intermediate conception "microscopic view of current".

Details of teaching and knowledge construction

The process of knowledge construction started with some teaching input given by the teacher in form of verbal information in small pieces during a dialogue of about 20 minutes (including 5 minutes of own writing by the students). The following excerpts from the transcript are analyzed with respect to the process of knowledge construction.

Our general assertion to be tested is the following:

Students make sense of the teaching input "electron" by using certain cognitive tools like "electron as a particle" or other cognitive tools from everyday life language like to travel, to stay, to push etc., thus constructing their new intermediate conception "microscopic view of electron current". On the one hand, we see some cognitive tools specifically related to electric circuits, like

- electron as a particle;
- charge (positive and negative); electrons are negatively charged; this might lead to repelling (forces) between them and to attracting (forces) from the positive end of the battery
- the battery has too many electrons (wants to get rid of them, wants to become neutral)
- movement is caused by attractive and repulsive forces (physics language).
- atoms are composed of electrons and protons; they are neutral.

On the other hand we see the following elements of everyday language contributing to knowledge construction of this intermediate conception in a similar way as schema:

- electrons can move, go up there, not stay there; electrons can travel, they can stop, go back (to the battery); the movement has a unique direction; they can keep going; they flow (in circular motion)
- electrons can push other electrons or atoms; they can be pushed; thus electrons make movement of atoms in bulb (which causes light production); and electrons themselves can be moved that way.
- number of electrons; the number of electrons can be seen the same moving in and out of bulb or battery (conservation)
- electrons need some room to move; nowhere to go means that no movement is possible
- movement is caused by pushing and pulling (everyday life language)
- amount of current is related to number of electrons
- it's like a machine

So language may be an important cognitive tool for knowledge construction. [19]

We now give some selected evidence for this process of knowledge construction.

The teacher starts introducing a new view of current, not meaning energy but related to motion of electrons. He starts drawing at the white board. He also talks about an idea that the atoms in the bulb get movement from the moving electrons. At this point one of the students makes the following contribution:

C: So. So, electrons are going up there. But they're not actually staying there? They're just causing them to move and then they're going right back out and they're (inaudible)

Here, "going up there" and "not actually staying there" show two intuitive ideas arising from applying everyday life language to the new idea of electron current, thus coming to some notion of conservation! The ideas of same amount of electrons coming in and going out and electrons causing atoms to move were used by the teacher before, so C's answer shows at least some intelligibility and resonance.

The next contributions of students are coming after a general question of the teacher about movement of electrons along the circuit and the amount of electrons:

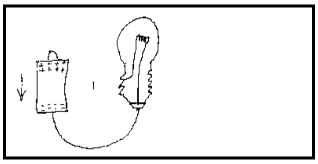
G: ...The electrons are going in there and it's moving the atoms. ... L: ...

C: The electrons are just moving 'em so that they light it. And then they're going right back out.

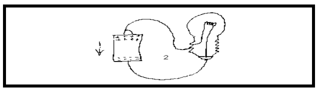
[19] "I think our ...language is the vehicle for thought....but don't introduce new language until the old is some cumbersome that you need a new word...see A. Aron on this." (E-mail contribution from Joseph Bellina (26.3.1995 on PHYSLRNR list)

These contributions again use elements of everyday life thinking, this time "moving the atoms", "to travel" [20] and "the same going out here", and thus again showing some conservation idea (which was missing later). Conservation seems easy from the particle view with electrons. But later - in session 2 - electrons can be used up, which perhaps is due to the fact, that there "electron" is used in a context which activates the prior conception "everyday life current".

Now the teacher starts with questions, for the first time using **transient state thinking** about the non-steady state**,** e.g. asking questions like "What is happening in the first moment after we make the connection?"



C: The electrons are going up there ... H: ...
C: And then they'll...Then they'll stop. H: ...C:...
G: Cause there's no place else for them to move.
C: That's it. Cause they don't have any place to move.
G: Cause they wanna keep on moving, just keep on going.
C: The bulb's gonna be...Um, negatively charged, and it's not gonna do anything. It's not gonna be equal, so it won't light.



The teacher goes on with the same idea of analyzing the transition state, now after closing the second connection: What's happening if we close it again?

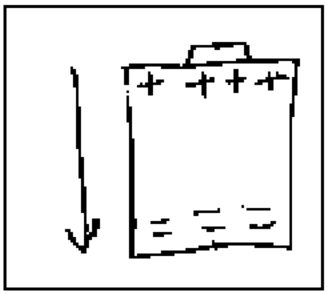
G: Now it has places to move. And go around. And so, by moving, that's why it's lit.
H: ... And why does it move?
{Pause of about 6 seconds}
G: (very silent) Because there's probably too many electrons in the battery.
H: ... G: ... C: ... L: ... H: ...
G: And so the battery wants to become neutral. So it keeps pushing all the electrons out. And then...But it keeps on getting right back in. Is that right?

Here we get many further resonances with the idea of "moving electrons". Again using it with intuitive ideas from everyday life ("to go up", "to stop", "no place to move", "keep on moving"). But in addition now "charge" from physics is used and "too many electrons in the battery" from everyday conceptions about current come into play. And G uses the next intuitive idea from everyday life ("pushing all the electrons out"), which provides a way of thinking along the lines of physics. In general this dialogue shows students to be ready for transient state thinking.

The teacher is now introducing ideas of pushing and repelling forces of equal and different charges. He finally asks: "If I draw + here, what does that mean?"

G: ...It's ...It's attracting them to the battery back.(moving with hand from bulb to (+) of battery)
L: And then they're just like, repelling off the electrons here.
C: And the extra ones will go down...
G: Oh, Yeah! Then it keeps just going, ...

Students seem to like ideas like "want to become neutral" or "attracted back to the positive", which are <u>not</u> introduced by the teacher. He was thinking of (+) as meaning smaller number of electrons. Repelling was used by teacher before but comes now in a new context from L. The whole dialogue is driven by spontaneous contributions from students: G - L - C - G - L - G. " It keeps just going" also is a new idea from everyday life, attached to "electron".



The teacher now gives some information about the battery pushing electrons from + to – . This idea seems to have a final impact on students' construction of the whole new conception of a microscopic view on current. They spontaneously contribute with new ideas and finally express good feelings of understanding:

C: It's like a machine. H: ....
L: So it goes...The protons are like, repelling.
C: Wow.

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[20] "To travel" could be called a "scheme" also. But we use "scheme" only in a stronger sense for cognitive tools playing a major role in thinking and knowledge construction, like "to share".

L: They're repelling 'em. And that's why they're going and pushing out. And then it, woosh, attracts back. And it repels 'em when they have too many.
C, G: Um-hum.H: ... C: Wow. G: That's cool.

This again shows some resonance by producing a new idea along the microscopic approach ("it's like a machine").

<u>Expression of good feelings of understanding</u>

We already showed the transcript part related to that above. The spontaneous idea "it's like a machine" and the emotional expressions like "wow" and "that's cool" give evidence that students had a feeling of understanding at the end of this dialogue.

<u>General description of new intermediate conception</u>

We summarize the findings form the knowledge construction analysis above and from more observations about the stability of this conception, shown below:

Intermediate conception "microscopic view of current" ("current 3")
Center (nucleus) of this conception: Protons stay, electrons move, in a circular motion, going from battery to bulb in one wire and back in the other (different directions). Motion of electrons makes movement in bulb and produces heat and light. The motion is driven by repelling and attracting forces from the battery. Conservation of number of electrons seems intelligible, but is <u>not</u> seen consistently as a rule, electrons still have the meaning of "fuel". Amount of current is <u>not</u> seen consistently in relation to speed of electrons

This conception can be more precisely characterized by facets, which are listed in appendix 1.

<u>Evidence for some stability</u>

In the first minutes of session two the teacher starts an open dialogue:
H: Do you remember this picture?
(The picture was left at the white board from last session)

After this opening question he only makes contributions like "Does it make any sense to you?" or "What do you think about it?" or repeating students' contributions. So basically all content of the talk is coming from students. Their contributions tell something about their intermediate conception after a break of two days:
C: In fact, I was explaining it to somebody. My roommate, or someone.
G: ... C: ... H: ... G: ... C: ....
G: The electrons move out through here into here. And when they get in here (bottom of bulb) they go up here (to the filament) and they create, um, energy. And...energy that moves it around to make it light up. And then it flows back into here (+ of battery) because, how come it's doing that, is because it's repelling out of here and it's getting attracted back to here.

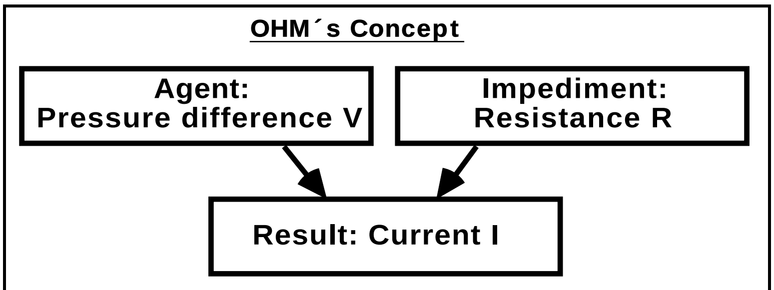
After discovering a little gap in there (pointing to a small interruption in the upper wire in the white board drawing), they add:
C: Well, it wouldn't light. ... H: ...
C: No. Because the electrons would have nowhere to go and they wouldn't have to move. ... H: ...
C: Because the electrons are moving down and going to there. It needs the positive and the negative, um, charges. I mean...charges? Are we talking about charges, here?

There is more evidence of some stability in session 2 when students are struggling with the pressure concept. They often prefer to use this first intermediate conception with moving electrons.

3.4 Intermediate conception "electron pressure" ("current 4")

<u>Teaching input, intention, context provided</u>

The teacher is heading towards qualitative and semi-quantitative explanations with pressure difference and current according to an Ohm's concept. The teacher has a dynamic view [21] of pressure and current in mind, but he does not explicitly explain it. The teacher expects intuitive thinking with pressure and pressure difference and there consequences for electron speed and amount of current.



Cognitive system aimed at.

The teaching style sometimes gets less constructivist with the pre-developed computer tutorial. But the development of own pressure models by students themselves for their own circuits seems to be a good contribution to foster their own reasoning, exchange of views and talking about.

Students do quite well in some intuitive reasoning with pressure (e.g. build up and release of pressure) and relating high pressure to negative and low pressure to positive; this might be a consequence of their first intermediate conception. But they do not always distinguish pressure and current and we see very little resonance to the idea of pressure difference and its relevance for understanding circuit behavior.

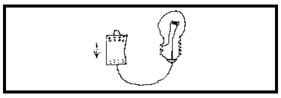
<u>Details of teaching and knowledge construction</u>

To introduce "pressure", the teacher had done some "preparation" with talking about "moving and pushing electrons" which - as we have seen already - unintendedly had resulted in a successful learning step leading to a new intermediate conception "microscopic view of current".

Now pressure is explicitly introduced near the end of the first session by the teacher. He is discussing a simple circuit at the white board and he again is using transient thinking with the question: What is happening in the first movement?

In addition he asks students to make use of the term pressure.

C: …
L: The pressure would build up inside. The bulb wasn't allowing any to expel out. There would be too much in there, and it would like, just,- H: ...



L. is using a new idea with build-up of pressure which was not used by the teacher before.

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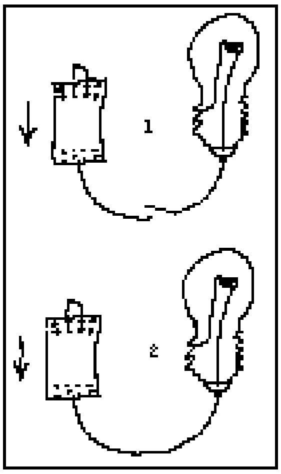
[21] "Dynamic view of pressure and current" means: pressure difference affects current, but current builds up pressure differences. This sometimes leads to non-stable states ("transient states") which change according to dynamical laws, eventually finally coming to a steady state. The latter is only intended by the teacher.



In the meanwhile the teacher has interrupted the wire between battery and bulb, and now suggests to close it, again discussing what is happening in the first moment. Students try to make sense of this situation with electron movement, hesitating to make use of the term pressure:

G: Now it's going into the bulb.
C: Now the pressure's over there. H: ...
L: It's starting to get too much.
H: Yes. And what is with pressure? Pressure is here and here. So, we have? C: ...
L: There's no release of pressure, though. There's gotta be some release to keep the, the movement flowing so that these continuing electrons keep going through the bulb.

The teacher again uses transient state thinking [22]. He does not explain pressure, he is expecting the word pressure to make sense by itself together with the example after the previous introduction of pushing and pulling forces. He especially is expecting some reasoning with a balance of two pressures ("pressure is here and here"). This idea gets no resonance from students. They do not start with reasoning about pressure difference. This is in perfect agreement to previous research results about students making sense of pressure by Engel Clough and Driver: "... but few pupils explained in terms of balancing pressures" (Driver et al. 1994, p.152). Instead, students go on intensively using the microscopic view with "electron" and "movement" and other ideas like push and pull connected with that: "they don't have anywhere to go", "the bulb wasn't allowing any to expel out", "there would be too much in there", "they wouldn't go anywhere", "they wanna repel from each other", "we get electrons here", "it's starting to get too much", "to keep the movement flowing", "electrons keep going through the bulb". [23]

But they already start connecting those ideas from the microscopic view to the term pressure: Lynn starts talking about "pressure would build up inside" - which in itself is an interesting intuitive idea - and is connecting that to "the bulb wasn't allowing any to expel out" and "there would be too much in there". And C in a similar way connects pressure to "too many electrons" and "it wouldn't go anywhere". And G connects "they have pressure because they wanna repel from each other". Lynn finally comes with a perfect idea relating release of pressure to the movement of electrons: "there's gotta be some release of pressure to keep the movement flowing, so that these continuing electrons keep going through the bulb." That means, there is a relation between a microscopic view of current and a conception of pressure! This was the hope of using this conception in this teaching approach. But often in later reasoning the conception of "pressure" by Lynn is reduced to the facet "high pressure at positive, normal pressure at bulb, low pressure at negative", used like a general rule.

Students seem not to grasp the idea of pressure balance or pressure difference. The teacher tries again and again to talk about high pressure at the battery and low pressure at the bulb in the beginning of the transient state, becoming high pressure at the end and to see a connection to movement. But students do not grasp that idea, they are talking about "it's just stuck" or "high pressure needs some release". They finally write down in their note book: "High pressure to low pressure makes them move" and "negative means high pressure, positive means low pressure."

Already at this point - the end of a short introduction of "pressure" in the first session - one thing seems clear: "negative pressure is higher than normal, positive pressure is lower pressure than normal". Our hypothesis is, this is due to the first intermediate conception "you need positive and negative currents". The new intermediate conception builds on the previous one.

The first use of "pressure" in session two comes from the teacher. Pointing to a diagram on the he asks "now this term pressure. Does this make sense to you?" One of the students reacts quite nicely:

C: Yeah. ...that's, like, the build-up of the electrons,

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[22] About the non-steady state, e.g. asking questions like "What is happening in the first moment after we make the connection?"

[23] Not all of these statements were shown in the cited part of dialogue.

talking about "the build-up of the electrons". But afterwards students only talk about electrons - not pressure - coming down there and being attached to their protons and being pushed by the chemical etc. Finally, they again come with high pressure at the negative end of the battery and low pressure at the positive. In addition, there is some idea that electrons move from high pressure to low pressure.

The "build up" idea seems one intuitive idea from everyday life with pressure which is quite frequently used and helpful. There are not too many ideas like this related to "pressure". The next idea of students "there's always gonna be a pressure, else it wouldn't move."(C) perhaps reveals a lot about students' thinking with pressure and its differences to physical thinking with pressure differences! The case of high pressure everywhere and no movement seems not to exist in this student's construction. But Lynn's proposition sounds a bit different: "Since they go from high pressure to low pressure."(L) This perhaps could open a thinking in differences.

Now the teacher for the first time uses "pressure difference", but only once. And he uses it in relation to resistance, having a "dynamic model" of pressure differences and current causing each other in his mind. And he explicitly asks weather this makes sense to them. The resonance from students seems weak. They are talking about "high pressure when it's coming out or flowing out" and "kind of a high pressure that's pulling them back ". Again, some properties like high pressure or pressure from attraction seem more powerful than any reasoning with pressure differences. It might be also due to some impatience of the teacher, but we interpret this - together with many other evidences - as showing some fundamental problem and non-resonance with the concept of pressure difference. There are previous research findings on students' conceptions about "pressure" which confirm this view. Séré found pupils thinking that only wind, not still air, has pressure. Engel Clough and Driver found pupils less inclined to think in terms of pressure acting in all directions. Atmospheric pressure pushing was mentioned but few pupils explained in terms of balancing pressures" (Driver et al. 1994, p.152)

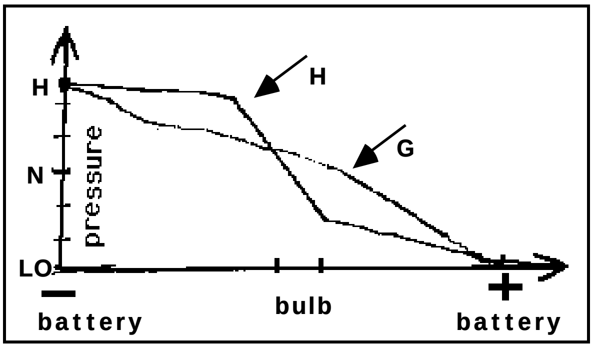
The teacher now continues working on pressure and pressure difference by asking students to draw a diagram.

The diagram drawn by G shows the same tendency:

> *G: Well, I would think it would go like this. It would just continue to decrease. ....*

Afterwards the teacher gives his diagram as a feedback.

> *H: I think in a different way. I paint it now. Let's see if you can make sense of my way to think of it.*



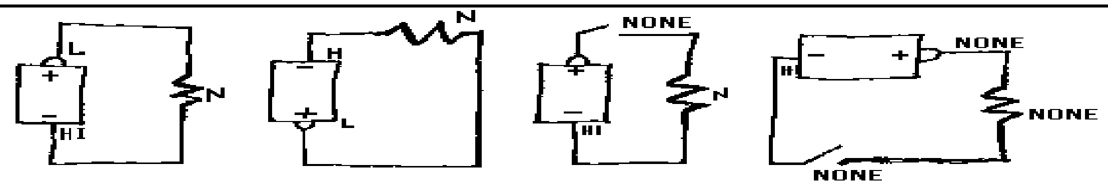
Decrease of pressure is just memorized and taken the most simple way. Two previous explanations of the teacher about main pressure difference over the lamp and about big pressure difference being due to big resistance had no resonance in students' construction shown in this drawing.

After this feedback the students only describe the differences "so it makes a pretty drastic drop right at the bulb" or "so it stays pretty high". The drastic drop and similar features are taken as facts but not connected to any own ideas and cognitive tools; it is not understood. The teacher again tries to push an intuitive understanding, "the bulb is the hardest part of the way", but students react as if this does not make much sense to them. While the teacher again uses the term difference this term is not used by students at all. They talk about pressure being "used up". Here a new facet about pressure drop is used which later in the learning process is clearly seen to be connected to the old idea in the prior conception of current consumption. This is a new way of making sense, using part of the old prior conception "everyday life current" now connecting it with pressure.

In their written explanations we find expressions like "then it hits the bulb and it uses up all the pressure to push the electrons through the bulb", which is perhaps half way of constructing the notion of pressure difference. This perhaps could be a key to better teaching. Lynn, in her next statement, stresses the "drop of pressure" which is quite helpful to learn more about "pressure loss" but - as is to be seen from many statements later-on - for Lynn also has the meaning of current consumption. In this statement both intermediate conceptions "microscopic view of current" and "pressure" come together, probably with a bias of the prior conception of "everyday life current".

The next activity is centered around a written text: "A battery (cell) is a device that tends to maintain a constant electron pressure difference across its terminals". Does this sentence make sense to you? The reactions of students to this sentence again are not showing any significant resonance with the term pressure difference. The teacher sometimes asks directly about students' meaning of pressure difference, but he only gets some statements about positive and negative being high and low pressure, but nothing related to a dynamic view in relation to current or pressure difference being a cause of current. Again, there is no good resonance to pressure difference. No word about a battery being the active part in a circuit and this is done by the pressure difference.

In the next task students are asked to label four circuits with H, N and L for high, normal, and low pressure. Students, when asked to explain, why the bulb is not light in the last two circuits only use the microscopic view of electrons and movement. L in addition uses her release of pressure idea, which clearly is one facet of her pressure conception, coming to "none" as a label for no pressure. But no idea of constant pressure and being no pressure difference.



Lynn's drawings

The next activity is started by student G, who starts to build a new circuit with two bulbs in series. After some time the circuit is working and students are talking:

L: It's sharing the current.

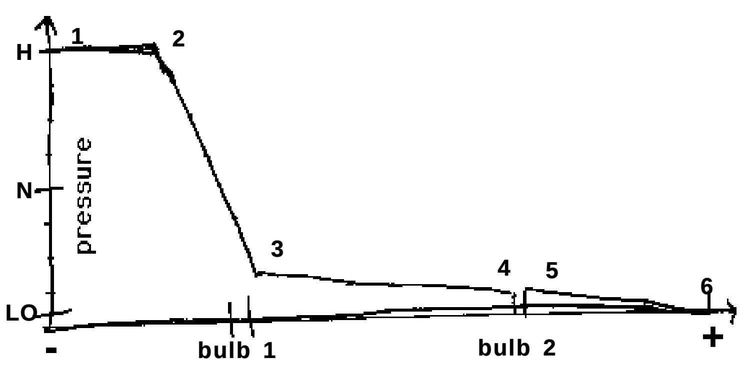
G: ... This high pressure goes through here. And then it uses a bunch of it at the bulb. We already decided that. ... And then it hasta go through and it hasta use more pressure. An we don't have as much pressure to give as we did over here. So it has to share.

L: ... But since this (1.bulb) is taking...pressure and electrons away from this...it's gonna dim this light. And then here (2.bulb) they hasta go again and then the electrons'll be pulled away again. So each time...

The teacher then asks: Would you like to draw a similar drawing like this?

L: ... there's gonna be...a decreasing pressure here. An all of a sudden it's gonna get to that bulb. And it's gonna take ... even more , so it's gonna...just keep...decreasing, I guess.

L: ... Okay, this high pressure's coming out here. And it's going in here and it lights this {the first bulb} up just fine. And it goes and goes and goes and oops! Golly! We have to have enough power. Here we are lowering down. We're going. We're going. Thinking we're going to get back to the battery. But no, now we have to light another bulb. So , it just kinda goes, "Oh, I need some help!" "Give me some of those electrons back." Or whatever. So then it kinda...takes away from...takes electrons from this to try to light this one.



L is drawing

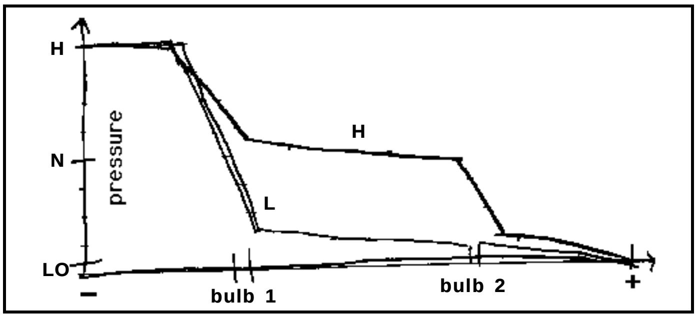
This is one example of a very <u>important case</u>: in a new context students typically use old cognitive tools - more accessible, confident, reliable, powerful, with more probability to be used.

Here the everyday life scheme "to share", which is closely related to the prior conception of "everyday life current" with its notion of current containing energy like fuel. And also typical:

"pressure" comes in after some time, after the teacher is putting only a general question "would you explain? " without any specific content hint. And again classical: the meaning of "pressure" seems to be very near - at first - to the prior conception meaning of "current". "This high pressure goes through here. And then it uses a bunch of it at the bulb." "And then it hasta go through and he hasta use more pressure. And we don't have as much pressure to give as we did over here. So it has to share."(G) This idea is very interesting because sharing the pressure is really an idea coming very near to physics!

After the feedback drawing from teacher (H), students are asking very good questions for explanation:

G: Cause it's not taking as much. But why doesn't it?
H: ...That's a really good question! It doesn't take the whole pressure.
G: Yeah. Why doesn't it, though?
H: ...
L: How does it know it's gonna need more?
H: ... {Pause about 7 seconds.)



The teacher gives a spontaneous explanation using <u>transient state thinking</u>, which is further explained by the following picture:

H: Well, let's assume this (points to L's drawing). Then a lot of current would come here. (Pointing to the point between the bulbs.) ... Because a big pressure difference makes a big current. ... Then, this current would <u>not</u> come through (pointing to the second bulb). So, the pressure would go up here (Pointing to the point between the bulbs.) . ...

We now try to **summarize** the whole process of knowledge construction by looking at teacher's ideas and formulate hypotheses about students' use of cognitive tools in relation to the context set by the teacher.

Teacher's ideas

1. Pressure and movement
   - The electrons will start and go over there (open circuit). And then this movement will stop. Why would it stop? Perhaps make use of the term pressure. (The teacher has a dynamical idea of pressure and current, thinking of high pressure building up throughout the bulb which would result in a "zero pressure difference" (balance of two equal pressures), thus resulting in "no more movement".)
   - Now we have high pressure here and high pressure here, and no more movement.
   - High pressure to low pressure makes them move.

2. Pressure difference
   - This wire is not a big resistance to the current. So it needs a little pressure difference from here to here for the current to come here
   - Going through the bulb needs a big pressure difference. Between the beginning and the end of the bulb. So that, with a big difference, the electrons are pushed through.
   - A big pressure difference makes a big current.
   - A battery (cell) is a device that tends to maintain a constant electron pressure difference across its terminals.
   - Pressure (in a syringe) is everywhere.

Students' ideas (cognitive tools)

1. Build up and release of pressure
   - The pressure would build up inside.
   - Too many electrons in there means pressure.
   - There's gotta be some release (of pressure) to keep the movement flowing.
2. Negative means high pressure, positive means low.
   - Negative pressure (electron pressure) is higher than normal; positive pressure is lower pressure than normal.
   - High pressure (at negative) because they're all being pushed down there.
   - As they're exiting, there's kind of a high pressure that's pulling them back down (to positive).
3. Pressure and movement
   - High pressure to low pressure makes them move.
   - There's always gonna be a pressure, else it wouldn't move.
   - This high pressure goes through here.
4. Pressure drop, pressure being used up
   - There is a drop of pressure along the bulb.
   - The pressure decreases as it goes down little by little.
   - The pressure is used up on the bulb.
   - It uses up all the pressure to push the electrons through the bulb.
   - To share pressure.
   - The first bulb is taking pressure and electrons away.
   - It hasta use more pressure.
   - It has to have enough pressure to light another bulb.
   - It takes pressure from here and brings it to here to light this bulb.
   - Pressure difference: the positive is low pressure and the negative's high
5. Special ideas
   - The chemical is causing the pressure.

The following ideas get **no resonance** in students' thinking:
- Pressure balance: two high pressures result in no movement.
- Pressure difference.
- Pressure in all directions; pressure in the backwards direction hinders movement.
- No Ohm's p-prim with force (p-difference), resistance and movement.

<u>Expression of good feelings of understanding</u>

There are rather expressions of negative feelings, like "it's...just kind-of a trick".

<u>General description of new intermediate conception</u>

The concept of pressure is already introduced at the end of session 1. So, at the end of this session three intermediate conceptions "it needs the positive and the negative", "microscopic view of current" and "pressure" coexist. They partly answer different questions but sometimes they are used altogether or one after another in one situation.

Intermediate conception

"current with electron pressure" ("current 4")

Center (nucleus) of this conception: Electrons go from high pressure to low pressure. High pressure is at the negative end of battery, normal in (or after) the bulb, low at the positive end of the battery. Pressure can be released or built up.

To describe this conception more comprehensive we use facets. Each facet can be compared to the scientific view. The facets are shown in appendix 1.

4. Conclusions

The results of the study give evidence for the fact that students come to new intermediate conceptions during their learning and construction process which are different from what the teacher expected or even realized. They start with a well-known preconception here called "everyday life current". After some experiments with battery and bulb and a task to formulate a general rule they are constructing an intermediate conception "positive and negative currents" which is similar to the well-known conception "clashing currents". It here appears after a substantial learning process as an intermediate conception showing some stability in the following teaching and learning process. Then the teacher starts to talk about electrons and their movement. For him this is only an introduction before using the concept of pressure which was the center of the teaching approach. Students very much resonate with the idea of moving electrons and contribute a lot of own ideas to this. They finally come to a new intermediate conception "microscopic view of current". The teacher then starts to introduce pressure and pressure difference. Students also contribute own ideas with pressure, for instance, the build-up of pressure and release of pressure. But we could find no resonance with balance of two pressures and coming to a dynamical view of pressure difference being the essential course for electron movement and current.

On the other hand we found some interesting resonance with the idea of transient state thinking, especially in the case of an open circuit and in the case of two bulbs in series. We agree with the view of Fredericksen and White (1991) and Steinberg (1987) that causal understanding of electric circuits can be promoted with an "aggregate flow model".

We finally want to formulate some hypotheses for improving teaching:

1. Using a particle model of current together with motion helps students a lot to make sense of it for their own. Thus improving understanding and knowledge construction.
2. Pressure is not by itself promoting students' understanding of voltage, especially because there is very little resonance with the idea of balance of pressures and pressure differences.
3. Transient state thinking - thinking what is happening in the first moment and how a steady state is reached - gets at least some strong resonance in students' thinking and coming to good questions.
4. Together with a particle model of current and the idea of transient state thinking the best idea of representing voltage would be either something like density of electrons or a field view. This question cannot be answered from this study.

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Students' conceptions and scientific concept of "current" **Appendix I**

	Prior conception "EDL current" ("current 1")	Intermediate conception "positive and negative currents" ("current 2")	Intermediate conception "microscopic view of current" ("current 3")	Facets of scientific concept "SCI current"
Facets of substance vs process	- substance "electricity"	- 2 substances: positive and negative charges, with 2 cables and 2 connecting points at battery and bulb	- electrons move, protons stay	- process of electron movement
Facets of energy	- containing energy (like fuel/food)	- positive and negative coming together is producing light	- motion of electrons makes movement in bulb and produces light	- transporting energy (like water)
Facets of motion	- electricity flows 'to' (movement necessary) - going one direction: battery - wire - bulb	- both charges flow 'to' (movement necessary) - both going one direction: battery-bulb	- electrons flow 'through' (movement necessary) - forming a circular motion	- electrons flow 'through' (movement <u>essential</u>) - forming a circular motion
Facets of conser-vation	- "something" is consumed	(- "something" is consumed)	- only partially using conservation of electrons	- with mass and flux conservation (electrons are <u>not</u> used up)
Facets of causes for motion	- battery is active, bulb passive	- battery is active, bulb passive	- driven by repelling and attracting forces from the battery	- driven by the pressure difference from the battery
Facets of amount of current	- amount of current is volume or strength of "electricity" being used up in the bulb	(- amount of current is volume or strength of charge being used up in the bulb)	- amount of current: more related to number of (consumed) electrons than to speed	- amount of current means: number <u>and</u> speed of moving electrons: I n v

Students' conceptions of "current with electron pressure" and scientific concept

	Intermediate conception "microscopic view of current" ("current 3")	Intermediate conception "current with electron pressure" ("current 4")	Facets of scientific concept "SCI current" and "pressure"
Facets of conser-vation	- only partially using conservation of electrons	- same, some improvement, but in some situations: "current"= pressure = pressure difference= number of electrons= power: all can be used up - pressure can be lost along the circuit - pressure can be split/shared	- with mass and flux conservation (electrons are not used up) - pressure shows typically a gradient
Facets of causes for motion	- driven by repelling and attracting forces from the battery	- driven by pressure from the battery, some effort to use p-difference - electrons go from high p. to low p. - attraction from positive is important - "pressure" itself perhaps has the meaning of pressure difference	- fluid or gas motion is maintained by a pressure gradient along pipes - the higher the pressure difference along a piece of pipe, the higher the speed and amount of current (law of Hagen-Poiseuille) - electrons are driven by the pressure difference of the battery - voltage relates to pressure difference
Facets of amount of current	- amount of c.: more related to number of (consumed) electrons than to speed	- same, some improvement to use speed	- amount of current means: number and speed of moving electrons: I = const. n v
Facets of amount of pressure	- not valid	- "high" pressure at negative, "normal" in the bulb, "low" at positive - pressure is a result of many (extra) electrons - high pressure is from repelling forces, low from attracting forces	- pressure of a gas is depending on particle density and temperature (movement)
Facets of dynamics of pressure	- not valid	+ pressure can be "built up" or "released" - pressure is released at an open end - an unconnected or interrupted wire is like a open end of a hose - pressure can diminish along one wire	- p. can be "built up" or "released" - pressure is released at an open end - an unconnected or interrupted wire is like a closed end of a hose - pressure can diminish along one wire