QUALITATIVE INTERPRETATION
OF A LEARNING PROCESS
IN ELECTRIC CIRCUITS

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1. Introduction

One of the outcomes of a recent international workshop on research in physics learning (Duit, Goldberg and Niedderer, 1992) was to give a high priority to investigations of "learning pathways" in all topics relevant for instruction. An important issue discussed at the workshop was the following question: What kind of cognitive entities are appropriate for describing learning processes? (Niedderer and Schecker, 1992) One possible answer to this question is to use an explicit description of "cognitive elements" in a "cognitive system" as constructions of researchers in the field. This would help science education to become a science of "what is in the mind" (Lawler 1987).

The research questions of the present study relate to this issue of appropriate cognitive elements in the domain of electric circuits:

- What are appropriate cognitive elements describing students' thinking during a learning process on electric circuits?
- Which of the teaching inputs had a comparatively high resonance in students' thinking and which had only a low resonance?

This research project represents the continued work of interpretation toward achieving the ultimate goal of describing the entire learning process.

2. Methodology

Three college students were selected randomly among some volunteers enrolled in a physics class for prospective elementary school teachers. Their instruction took place in a special room with video and computer equipment. The study thus was a clinical study, with the researcher also being the instructor. Each of the six 90 minute sessions over 3 weeks was videotaped with two cameras, one aimed at the students and the other aimed either at the computer screen or the experimental apparatus. Nearly all dialogues were transcribed resulting in about 400 pages of transcripts.[3] The study also had some aspects of a natural setting: the instruction occurred during the same time, with the same sequence of experiments, with nearly the same topics, and with the same tests as IN the regular class.

From a methodological point of view, it was a learning process study with single students, with aspects of both a natural and clinical setting, lasting about nine hours, over a three week period.

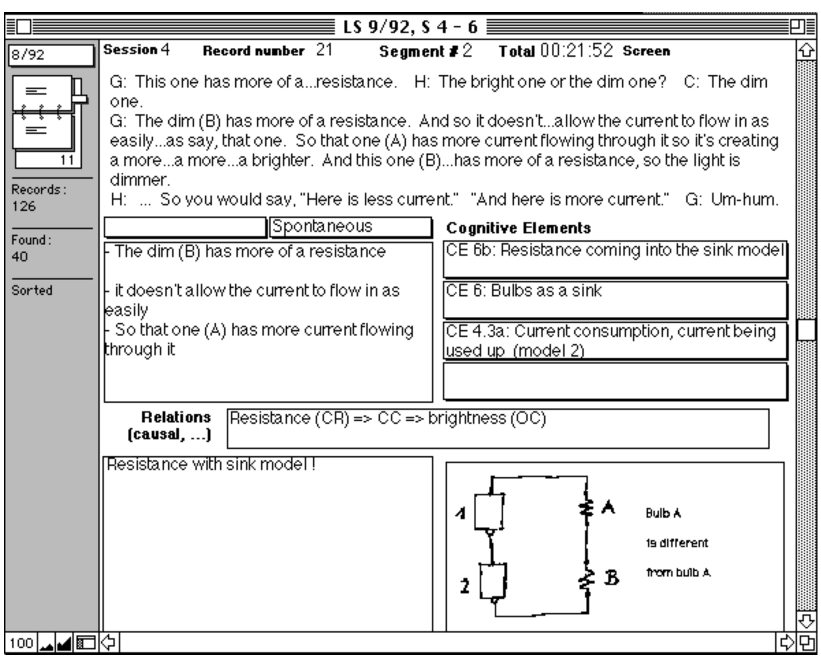
[3] The transcripts were done by Joy Massa

3. Instruction

The *instructional process* was guided by the following major ideas:
- Use of open-ended hands-on experiments with batteries and bulbs.
- Teaching electric circuits with an electron gas pressure model.
- Use of a computer-videodisk software program, which provided a tool for representing students' own ideas about pressure on the screen, thus promoting both their own thinking and discussions between the students.
- Student oriented teaching, with a first phase always related to elicitation of students own ideas.

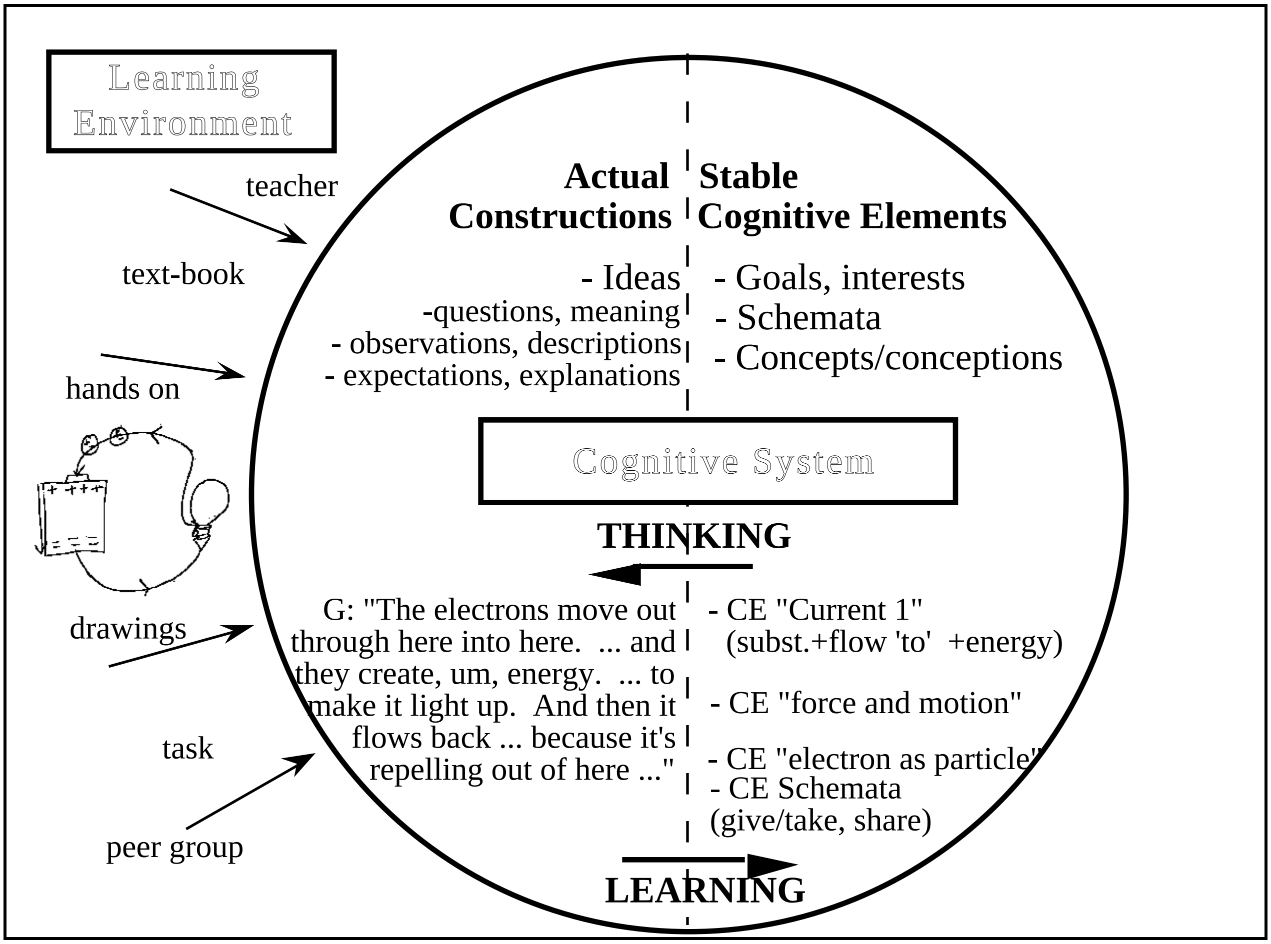
4. Qualitative interpretive analysis

A qualitative database has been established to promote an iterative interpretation process. The powerful software used to analyze the data was FileMaker by Claris. Hypotheses of "cognitive elements" have been defined on the basis of the previous research results of many other researchers (McDermott 1991; Duit, Jung, v. Rhoeneck 1985; Frederiksen and White 1991; Shipstone et. al. 1988; Heller and Finley 1992).
The process then goes on looking at the data with these first hypotheses, making changes in the hypotheses, finding new ones, and carefully looking for evidence and counter evidence in the data. Results then are reported formulating the final hypotheses and selected pieces of data giving evidence and/or counter evidence. The aim is to describe a cognitive system for electric circuits as a hypothetical construct to describe and explain students' thinking and learning. The following picture shows one of more than 200 records of the new database, representing one student's statements and the cognitive elements assigned to it in an interpretive process:



<u>5. General view of the learning process</u>

5.1 Theoretical background: The idea of a cognitive system



This idea of an explicit formulation of hypothetical models of the cognitive system was formulated in more detail in an earlier paper (Niedderer, Schecker 1992). Our concept of "cognitive elements" is related to a subject matter oriented pragmatic approach. It tries to define those cognitive elements from a content based view. The description of those cognitive elements is a theoretical construct of the researcher which meets the main criterion to be able to explain as much as possible how processes of thinking and learning work. In addition, we try to take into account more general cognitive elements such as schemata, general frames of thinking, interests, and epistemological beliefs of students. In this special study we are mainly focusing on those cognitive elements which are closely related to the special content area of electric circuits. More general frames of thinking (such as local reasoning versus systems thinking) and epistemological beliefs (such as context dependent versus general explanations and consistency) will be reported later.

5.2 The starting point: What are stable cognitive elements prior to instruction?

(e.g. the alternative concept "current 1")

From empirical research many facets of students' alternative views on electric current are well known (Duit, Jung, Rhöneck (1985), Dupin, Joshua (1987) Fredette, Lochhead (1980), Schwedes, Schmidt (1992)).

From previous research in the Bremen group (Schecker 1985, Niedderer 1987) we are coming to a broader view of students' alternative concept current called "current 1" in this study. This broader view is based on the following reasons:

- From epistemological considerations it seems clear that concepts are used in different ways in scientific and everyday domain (Niedderer 1987, Reif, Larkin 1992). We see the important difference with respect to the concept current that in everyday life the concept has wake general meaning which becomes more precise in a specific context. Thus, the concept current seems to be related to a general understanding of something which is given from the source to the consumer. This structure is used in everyday life all the time, plugging in electrical devices of many kinds to the electrical source. So, electrical current in this context has a meaning of "something" which is given from the source to the consumer (concept "current 1"). On the contrary, in the scientific view current is generally and sharply defined by the amount of moving charges and their speed.
- Related to these epistemological considerations we empirically, in the area of mechanics, found a "cluster concept force" (Schecker 1985). So, from this point of view it seems very likely to look for a "cluster concept current".
- Our view to students' concept of current is related to the view of Schwedes and Schmidt (1992). They see the "consumption concept" as a nucleus of students' mental model. They want to promote a conceptual change to a different mental model organized by an "Ohm's concept".
- Looking with this view to our own data we come to a lot of new evidence for this view.

5.3 A general model of the learning process: the role of prior cognitive elements, teaching inputs and intermediate states

The starting point of students is a lot of experiences with using electrical apparatus, that means to have some source of electrical energy, some connections with a cable and many different devices using this electrical current. On the other hand, there is very little experience with own experiments with bulbs and batteries, with questions like different kinds of circuits, different brightness of bulbs, resistance and so on. We assume the following types of stable **"cognitive elements" (CE)** to summarize this pre-instructional experience:

- Cognitive elements specifically related to electric circuits, e.g. the cognitive element "current 1"
- Cognitive elements from mechanics, applied to reasoning with the movement of electrons (microscopic view), e.g. force and motion
- Cognitive elements from other areas, e.g. schemata like TO GIVE, TO SHARE.

These cognitive elements are used as cognitive tools to make sense of all what could be called the **"teaching input" (TI)**. This teaching input contains the following types of information:
- Experiments with electric circuits, combined with the task of prediction, observation and explanation. Every task of this type ends with some feedback and explanation.
- Special texts written for the instructional process (e.g. "What does the steady current situation look like?" or "Basic structure of electric circuits").
- Verbal explanations of the teacher, sometimes combined with white board drawings, mostly at the end of a teaching segment.

So during instruction students get the chance to have new experiences with "hands-on" experiments they have never seen, and they are guided to use new concepts, one of which is "current" which in their pre-view has a different meaning. So, in our view learning in this instruction hypothetically contains the following **types of learning processes:**

- Developing new ideas and "intermediate states" by applying "old" cognitive elements to new experiences
- Developing a new intermediate state "microscopic view with electrons" from teaching input and old cognitive elements.
- Changing the meaning of the concept "current" (conceptual change from "current 1" to "current 2")
- Developing meaning for the new concept "pressure" given by instruction and trying to make sense of it related to old cognitive elements, old experiences, new experiences, and teaching input.

Students in these processes construct **new ideas**, coming from "old" cognitive elements working in new situations. Some of these ideas seem to be especially stable and often used; we call those ideas **"intermediate states" (IS)**. They are "intermediate" in a double sense:
- they are current constructions, not yet as stable as "cognitive elements", but more stable as other spontaneous ideas; they are candidates for stable changes in the cognitive structure of students, thus describing learning processes.
- they are in between prior alternative conceptions and the scientific concepts; not really what was intended by instruction, but some progress in students' minds.

5.4 Related theoretical views

The conceptual change model as it is used by **Hewson, Hewson (1992)** distinguishes between new and existing conceptions. This relates to our old and new cognitive elements. "A key factor in the learning process is the status (Hewson 1981) that new and existing conceptions have for the learner". This relates to our result that students in our study in session 5 use different cognitive elements one after the other to explain one experiment (Niedderer, Goldberg 1992). Our observation is that students often start with the old cognitive elements, and after some time and discussions, come to apply the new developed cognitive elements. The aim of our learning process study is more to "identify representations of conceptions" (Hewson, Hewson 1992, p. 62) and not so much related to find out the changes of status of these conceptions.

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.

Brown and Clement (1992) talk about "intermediate concepts as stepping stones". This is exactly the same idea: Students develop their own versions of concepts here called intermediate concepts, and this has to be seen not as to be avoided but as a necessary "stepping stone" in a learning process. They give very nice examples of those intermediate states. They observe a "hold back tendency" and a "keeps going tendency" as different notions which in physics are generalized to the concept of inertia.

Schwedes and Schmidt (1992) in their description of the consumption concept with "consumption" being the nucleus of the whole concept are very near to what we call the cognitive element "current 1". The differences here lie in some details of description whereas Schwedes and Schmidt see a "chronological structure" as the central part of their consumption concept, we see the "current 1" concept determined by the everyday experience of a source, a transport from source to consumer, and a consumer giving some type of energy. We believe that current in students' minds is more related to fuel than to water.

Galili, Bendall, Goldberg (1993) in "The effects of prior knowledge ..." 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 to use ray diagrams.

6. Results

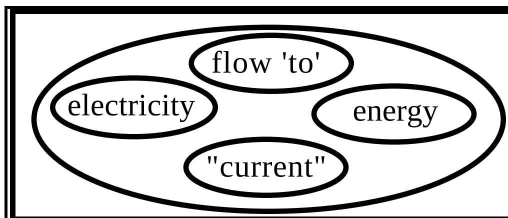
The results are described in an interpretive way showing interpretive assertions with constructed theoretical terms such as "cognitive elements (CE)", "intermediate states of learning (IS)" and "teaching inputs (TI)". The supporting data are given as parts of the transcripts. These parts are written in Italics. The numbers in brackets identify the part of the instructional process. As an example (2;4) means segment 4 of session 2. C, G and L are the short names of the three students, H the name of the teacher.

6.1 Description of the initial cognitive system

6.1.1 Cognitive elements specifically related to electric circuits

CE "Current 1"

Originally, "current" by the students is seen as a cluster concept with elements being
- "electricity" (substance like fuel),
- "movement" (flow 'to', not flow 'through'), and
- "energy".



Cluster concept "current 1"

This element is used extensively throughout the whole process giving its meaning to the words "current" and "pressure". That means that these concepts get a bias which relates them directly to effects like brightness of bulbs, number of bulbs and batteries, no matter whether there is a parallel or series circuit.

Some evidence from other research results

There seems to be a basic concept **"current 1"** which has a combined meaning of electricity and current and energy , as well as of substance and flow (Dupin & Joshua 1987, Solomon 1988). We call concepts like this with a broad range of interrelated meanings a "cluster concept" (Schecker 1985, Niedderer 1987). "Flow" here only has the meaning of "coming to", nothing about a closed circuit system, current to be there, like fire or fuel. This kind of "cluster concept" is not easily applied to **"current 2"** as being conserved (continuity), having the main meaning of movement, which is determined by forces and resistance to these forces. The concept "current 1" also seems to be related to a "source - sink model", meaning that current (electricity) is traveling from source (battery) to sink (bulb) (Fredette, Lochhead 1980). In an investigation of pupils' view on electricity Solomon (1985) asked students (11 to 14 years of age) about their agreement to similes. Some results were: Electricity is like a fire (about 60%), like a river (about 60 %), like a dangerous animal (about 85%), like a fuel (about 75 %), and like a lot of particles (about 35%). So these students do not primarily think of electricity in terms of flow. "It is interesting to note that several first-year pupils reject the river simile precisely because they thought that electricity does *not* flow. ... the results do cast serious doubt on the supposition of Osborne (1980) and others that young and uninstructed children already have a 'flow' model of electric current. It might well be that the notion of a live but static electricity in household cables precedes that of flowing. " Dupin and Joshua (1987) hold a similar view: "Electric current is considered (by students) as a kind of fluid enclosed in pipes. But the nature of this fluid is ambiguous, it could be said 'mixed'. Described from a physicist's standpoint, this fluid is made up of a material aspect and an energy aspect. ... Without distinguishing between these two aspects, it would be difficult to understand how the same fluid can be 'consumed' under its energy aspect and 'conserved' (under its material aspect)."

Voss (1991) also takes the view, that students' understanding of current is more related to a "substance schema" than to a notion of current being related to a "process schema". Students tend to see current as a passive substance which can be saved, transferred, and consumed. They do not view at current as a process , but as a substance instead.

A consequence of this view is a different interpretation of some of students' statements. E.g. an actual construction of students "the current is smaller as the number of bulbs increases" can be derived from this view of "current" and is not necessarily coming from an Ohm's type of thinking. The same is true taking a circuit with two batteries instead of one: the more batteries the more current (compare Minstrell's facet "the more ... the more ...", Minstrell 1992). Especially all those statements can be arrived if we assume that students think of a battery as a constant current supply. But we are not sure, whether this assumption is even necessary for the students.

The cognitive element CE1 also has a considerable affinity to sequential reasoning and local reasoning: if current is viewed as a supply of energy or "fuel", local and sequential reasoning are somehow adequate.

Special alternative conceptions known from research related to this cognitive element "current 1" are:

- Current consumption
- Battery as constant current source
- Bulbs as a sink

Current consumption

"Something" is used up along the circuit, preferably a part of current. With two bulbs in series the first is expected to be brighter than the second. Batteries get used up, they are giving something to make the bulbs light, so electricity is used up.

Battery as a constant current supply

In this well-known alternative conception a specific meaning of "current 1" is revealed: the current is "given by" the battery. That means: the battery determines the flow of electricity. It gives a certain amount of electricity which is divided amongst all bulbs. This amount is independent of the number and kind of bulbs.

Bulbs as a sink
This means the **bulb** is determining the amount of current "to flow into" the bulb. The bulb takes as much current "as it needs" (Voss 1991, 278), thus controlling the flow to a single bulb, no second connection is needed to take out the current to go on in the circuit. Brightness of a bulb is greater if its resistance is smaller. Resistance is perhaps not used before teaching, it seems to be integrated in the electricity-energy view, but it is readily connected with this sink model (Fredette 1981).

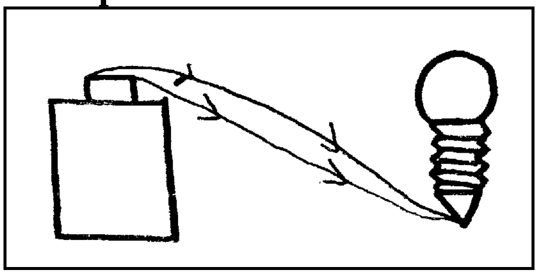
Evidences for the cognitive element "current 1" from this study
One main emphasis out of the results of this study is to distinguish carefully between two meanings of current, called cognitive element "current 1", and physics concept "current 2":

Cognitive element "Current 1"	Physics concept "Current 2"
- substance - flow 'to' (movement necessary)	- process - flow 'through' (movement essential)
- going one way: battery - wire - bulb - "something" is consumed	- forming a circular motion with mass and flux conservation
- containing energy (like fuel)	- transporting energy (like water)
- sink model of resistance (more resistance - less current flows into a single bulb)	- resistance as impediment to the circuit current as a whole
- amount of current means: volume or strength of "electricity" (current)	- amount of current means: number and speed of moving electrons

One important point is the following: **both** concepts contain an element of "movement" or "flow". But it is essentially different: in "current 1" it is only a necessary condition to bring the electricity to the bulb whereas in "current 2" movement and speed are characteristic and determine even the amount of current! A similar problem is given with the structure battery - wire - bulb. It sounds very similar to a "closed circuit" condition, yet it is connected with a very different meaning of "current". This is also the reason for the famous and well-known notion of current consumption: **"Something" is used up** along the circuit, preferably a part of current (but this is easily changed to pressure or electricity or energy, see above).

Three examples from the very first questions on "prior ideas about electricity"

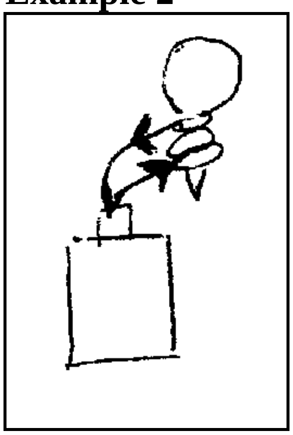
Example 1



C: I think it will glow because the battery will produce energy in the wire and will turn on the light.
I think electricity is moving from the battery to the bulb, causing it to glow.
I don't think we will be able to see this movement because I think it is inside the wires.

C uses the structure battery - energy, wire - turn on the light. And she is talking about "electricity" "moving to" the bulb, causing it to glow. Here, clearly electricity as a substance is seen to flow (movement) 'to' the bulb, giving energy to it and thereby causing it to glow. She seems also interested to see this movement perhaps hoping to clear all puzzles of electricity.

Example 2

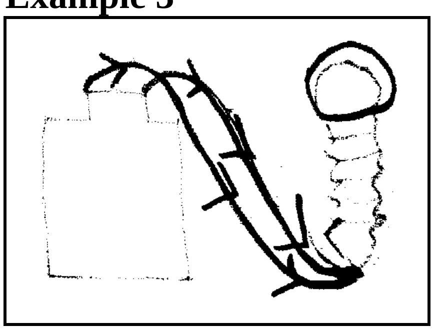


*G: The electrical **currents** from the battery go through the wire to the bulb. Thus creating an energy that makes the bulb light.*

*Yes, the **electricity** is moving through the wires. Through one wire the electricity is flowing into the bulb & the other takes the excess out. Making it a complete circuit.*

G is also using the structure battery - wire - bulb, **creating** an energy. Electricity is "moving through" the wires, flowing "into" the bulb, only the excess coming out.

Example 3



L: The electricity /power from the battery will flow through the wires and will conduct the materials at the bottom of the bulb. Perhaps one wire is neg. and one positive like the cables when you jump a car battery.

Electrical currents are moving through the wires.

All 3 students use a general concept "current" related to energy, power and electricity. All 3 use some conception based on the structure "flow from battery through wire to the bulb". All 3 use some concept of movement which is related to bringing the electricity from the battery through the wire to the bulb, not seeing the speed of the movement as the essential category.

6.1.2 Cognitive elements from mechanics

CE: Force and motion

Alternative frameworks about force and motion are well known from many research results. The most important part of those conceptions is the idea, similar to Aristotelian physics, that force in a motion is related to speed, and not to acceleration as in Newtonian physics. This idea, in electric circuits, is very fruitful because here we have a sort of motion with friction which is really obeying a law "speed proportional to force". We believe that this well known cognitive element and the fact that it describes in a correct manner the relation between voltage and current is the main reason why this cognitive element together with the corresponding teaching input about electrons moving through batteries, wires, and bulbs is perhaps the most effective part of our learning process.

6.1.3 Cognitive elements from other areas

CE: Electron as a microscopic particle

There is some evidence from research on students' conceptions in atomic physics (Bethge 1988, Lichtfeldt 1991) that students are very familiar with the idea of an electron being a particle which follows mechanical laws, especially having a trajectory and a speed in every moment and following the basic laws of motion and force.

Evidence out of this study can be seen from the easy acceptance of reasoning with electrons, especially after ideas about electrons and their movement have been introduced in session 1. Students afterwards tend to use this cognitive element by their own, even in many situations where it was not expected (see 6.3.2).

CE: TO SHARE, TO GIVE

Maichle (1981) already suggested that a schema TO GIVE is the central idea of students dealing with electric circuits. This idea in fact is closely related to what we have defined as a cognitive element "current 1" above seeing the notion of current being given from the source through the wires to the bulb as the central idea giving meaning to the concept current in clean structural conceptions. Voss (1991) has analyzed the role of other schemata for the thinking in electric circuits. He lists schemata like "substance", "to give/to take", "transfer", "consumption", "impediment", "transformation", and "to share", always with examples how they are used in everyday life language and with examples how they are used by students reasoning about electric circuits. So in this study we assume that, especially schemata like substance, to give, to share, to be consumed, are of relevant importance in understanding students' thinking and learning processes.

6.2 Selected Teaching Inputs (TI)

The instructional process was built up of about 50 activities in six sessions. Most of the activities were built around some type of new circuits, students working with the circuit themselves or with some computer representation. Their task generally was to predict, observe and explain those circuits. In every case they got a feedback about the correct solution at the end. In addition to this information students got basic texts and, of course, verbal explanations from the teacher. The whole teaching strategy was aimed at giving the opportunity to students to develop their own ideas and to be somewhat reluctant with teachers' explanations (student oriented teaching strategy), as has already been mentioned in part III above.

In this chapter we try to specify in more detail the input of teaching information by experiments, computer, the teacher, by texts, and by other types of feedback (e.g. written explanations of the students themselves after a final discussion) in the following crucial areas: current, microscopic view, and pressure.

<u>TI current 2</u>

The teaching input related to a physics concept of current in our instructional process of that time was not very explicit. The underlying assumption was that current is a trivial concept to understand. In the computer video software of that version there was no representation for current at all. This was changed in later versions where pressure was represented by thickness of wires and the amount of current was represented by arrows parallel to the wires. In the text "Basic structure of electric circuit" given to the students in session 4, there are the following two sentences related to current: "Current is 'stiff' and incompressible flow of electrons, that means that electrons move simultaneously at every part of the circuit. Therefore you have the same amount of current in every point of a closed circuit." And: "The amount of current is related to the speed of the moving electrons. A measure of the amount of current is Amps." This latter sentence was printed in small letters only. Seen from today's perspective this information about current was not clear enough and not at all related to students' view of current, namely "current 1" (see above). The following explanations of the teacher in this session perhaps came too late:

> *H: Why this one is brighter. Yeah. Well, let's assume what is written on page one.* ***Current is a stiff, incompressible flow of electricity.*** *Everywhere the same. ... All through the circuit. We have the same current. That means the same speed here. The same speed here. (4;2)*
> *H: ... Though it's faster than it was before. More current. More current means faster. You should always bear that in mind. More current means faster movement. (4;2)*

TI electron density, movement, forces

The teaching input about electrons and their density, their movement and forces in this study was given only verbally by the teacher, but already in session 1, segment 6. It was combined with a white-board drawing of the electrons moving through the wires and their high density at the negative end of the battery and low density at the positive end.

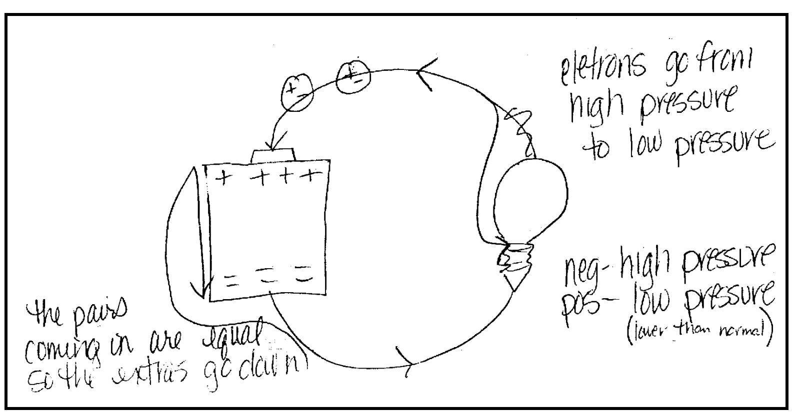
> *H: There are positive and negative charges. And the negative charges are moving; the positive charges are not moveable. They stay where they stay. The idea is the electrons are moving through this wire. And by moving they hit those atoms which are in this wire. This makes the wire gets warm and glows. So, if the movement is the essential thing, they have to have one wire where they can come in and another wire where they can come out. Otherwise no movement is possible.*

TI pressure

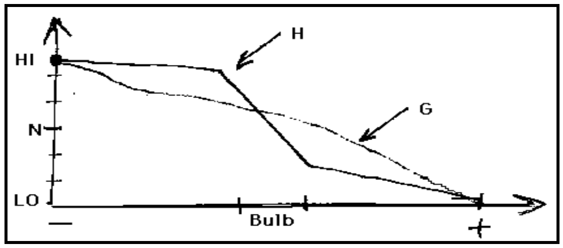
The introduction of a microscopic view with electrons (see above) was combined with the introduction with the pressure concept in session 1, segment 7:

> *H: It's so crowded here, they push each other. You have seen a repelling force from equal charges in those experiments with the spoon. They push each other in the direction where there are not so many electrons, at the beginning. And here are even less. The battery has to have some extra power -it is chemical- to bring the electrons against the electrostatic force from up to down. Always, the electrons go from high pressure to low pressure.*
> *G: (High) pressure from battery to low press. light bulb, to (high) press.& (low) press. top of battery. ...*

In the next segment (1;7) a diagram of pressure in a circuit with one bulb was drawn. An explanation from the teacher had been given already in the previous segment (see above):



The introduction of pressure was continued with a discussion around the following diagram, showing pressure in a circuit with one bulb (2;4):

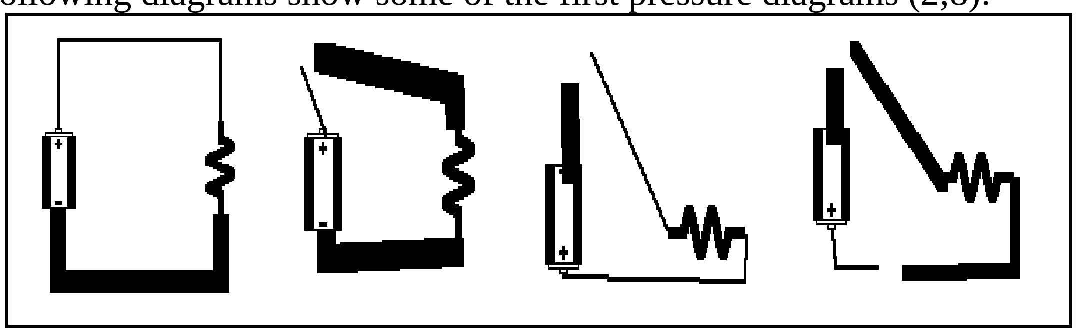


The introduction of an electron pressure model was continued with teacher's explanations and a text (2;5):"A battery (cell) is a device that tends to maintain a constant electron pressure difference across its terminals".

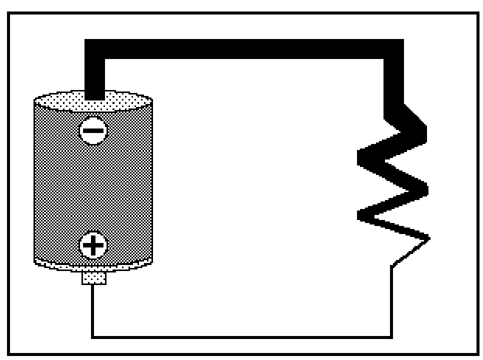
The introduction was further continued with the following task(2;6):
Use the following symbols to indicate the electron pressure at different places in the circuits drawn below:

HI	for	"high electron pressure"
N	for	"normal electron pressure", "neutral"
LO	for	"low electron pressure"

The following diagrams show some of the first pressure diagrams (2;8):



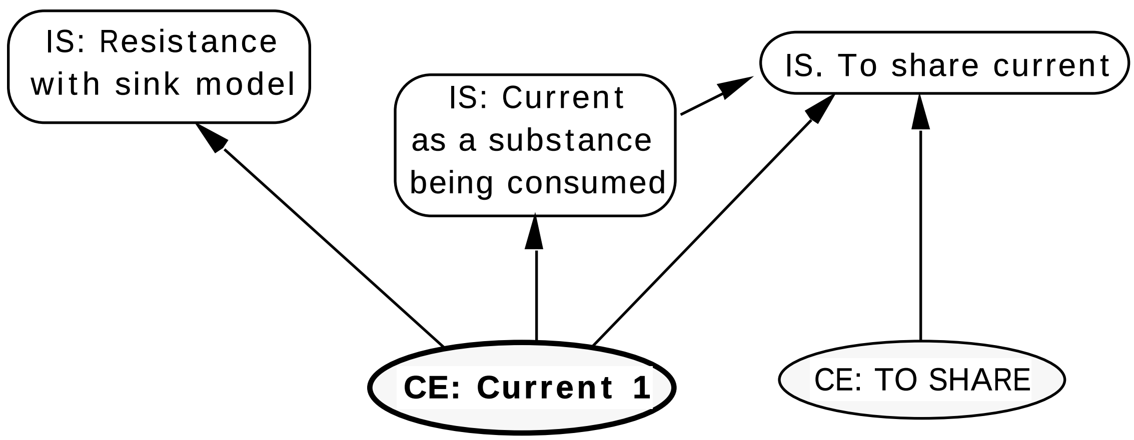
The introduction of pressure was going on with another text in session 3, segment 2, "What does the steady current situation look like?", which also had its main emphasis on pressure and "loss of pressure".



6.3 The Learning Process

6.3.1 Developing new ideas and intermediate states by applying "old" cognitive elements to new experiences

About 110 examples of students' statements were found throughout the whole study, in which the idea of students was related to the pre-concept "current 1". We will not follow all these examples here. But in analyzing our data we found all the well-known parts of this preconcept "current 1": current consumption, sharing current, battery as a constant current source, and bulb as a sink. We formulate three intermediate states out of this analysis which seem to be of some importance in analyzing the learning process: "current consumption", "sharing current" and "resistance with sink model".



Learning process, developing intermediate states (IS) from old cognitive elements (CE) and new experience

We give only few examples from our data later in the study, because this kind of processes are well-known from other research. But we want to keep in mind that these processes are very relevant learning processes which have to be seen as a kind of exploring new experiences with old cognitive elements, using them as cognitive tools to make sense of them. This might well be a necessary pre-condition for being able to adjust new concepts and conceptions to these new experiences.

IS: Current consumption

For lack of space and time no examples out of our study are presented. But there are many.

<u>IS: To share the current</u>

Example 1

The first example is from the first encounter with two bulbs in series in session 2, resulting from a spontaneous idea for this experiment of one student:

> *H: (You want) to put a bulb in it. (A second bulb in series)*
> *G: That makes two bulbs. (G starts to build in a second bulb) G: It's very dimly light now .*
> *L: It's sharing the current. (2; 7a)*

But already in this situation the new concept of pressure is used together with the idea of sharing. This was before using the computer-video pressure diagrams:

> *H: Would you explain? What do you mean by sharing the current?*
> *G: Because it has to go in through...It goes in here, okay? This high pressure goes through here. And then it uses a bunch of it at the bulb. We already decided that. And, so when it's coming through here (second bulb), it's still kinda lagging, it's kinda lagging. And then it hasta go through and he hasta use more pressure. An we don't have as much pressure to give as we did over here. So it has to share.*

A few sentences later it is explained even more clearly by the third student:

> *H: So sharing the current. What does that mean?*
> *C: Well, the current is now having to light two bulbs, instead of just one. So the two bulbs are sharing the current that's coming from the thing.*

Here C clearly has the well-known conception of current in a series circuit being shared between both bulbs.

Example 2

Our next example is from session 4. In the same experiment as above the bulb A is shortened, so bulb B is brighter. The answer shows that the idea of sharing was there before as an implicit understanding of the situation with two bulbs:

> *G: (Laugh) Now it's brighter.*
> *C: Because it's not sharing. I don't know. ... It's not sharing currents with the other light. (4; 1)*

Example 3

The next example is later in the same session, with a different circuit being proposed with 5 bulbs in series:

> *H: Yes. What will happen if we bring 5 bulbs in series here?*
> *L: The resistance is gonna be greater.*
> *G: (In unison with L) They're all gonna become dim. They're all gonna be dimmer. (4;2)*

Here we suppose that students use a mixture between a correct conception of resistance and its influence on current together with the old notion of current being shared between the 5 bulbs and therefore the bulbs being dimmer than before.

Example 4

This example clearly shows how "to share" is still used for pressure in session 5 in a new situation with a mixed circuit:

> *L: Okay, so the current. How about the pressure, though. Cause that's what I was getting confused. I was talking about pressure, here. I thought they were sharing the amount of pressure that was pulling it through. (5; 2)*

IS: Resistance with sink model

This intermediate state "resistance with think model" was explained in more detail in our last year's paper. It means that students think of current going into a bulb, and the amount of current is determined by the resistance of this bulb only. No thought is given whether a current is going out again and what that means to the whole system. We believe that this idea is also very much related to the basic concept "current 1".

Example 1

> *G: This one has more of a...resistance. H: The bright one or the dim one?*
> *C: The dim one.*
> *G: The dim (B) has more of a resistance. And so it doesn't...allow the current to flow in as easily...as say, that one. So that one (A) has more current flowing through it so it's creating a more...a more...a brighter. And this one (B)...has more of a resistance, so the light is dimmer. (4;2)*

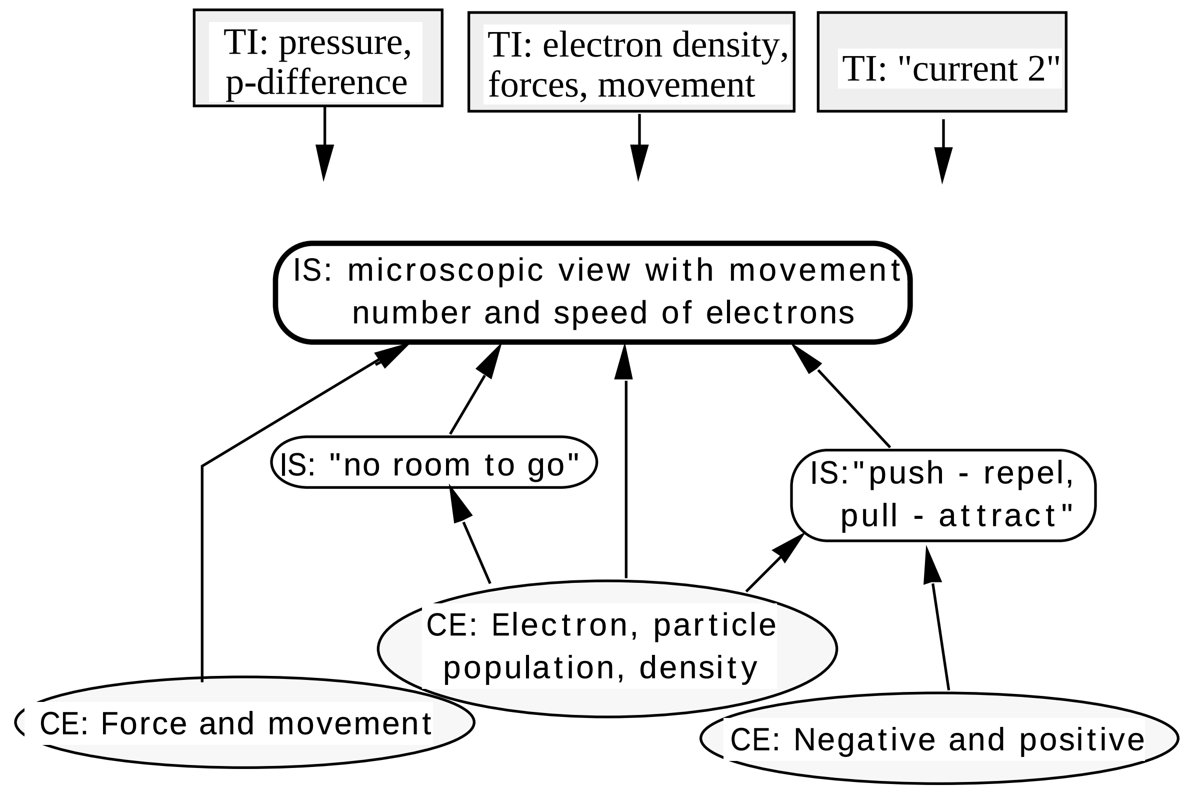
Later, she shows more clearly that this idea of resistance with sink model is related to the cognitive element "current 1":

> *G: And so more...more resistance equals less power...less pressure. (4;2)*

6.3.2 Developing a new intermediate state "microscopic view with electrons" with teaching input and old cognitive elements.

In part 6.1 we have described some cognitive elements related to the notion of an electron, its force and movement and having a negative charge. In 6.2 we described briefly how this microscopic view with electrons was introduced. Here we want to show some examples how students grasp this idea of microscopic view of processes in an electric circuit.

At first we give an overview of the whole situation in the following picture:



Learning process with "microscopic view": developing "intermediate states" (IS) from prior cognitive elements (CE) and teaching input (TI)

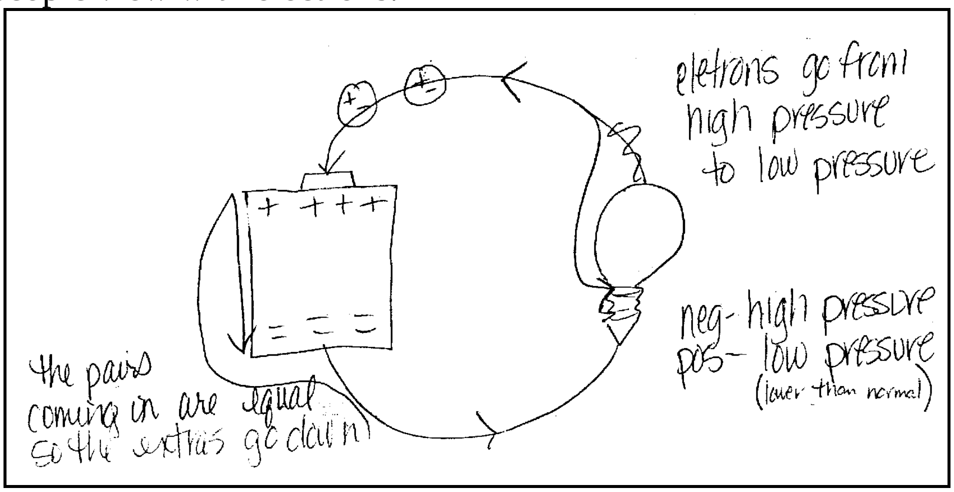
At the basis you see three cognitive elements (CE) which have been described in more detail in 6.1 and which we assume to be very stable and well-known in students' minds. Then we see two ideas used quite easy and often by the students, "push-repel, pull-attract" and "no room to go". We see students arguing by the help of those ideas to understand circuit behavior. Finally, we believe that this comes to an even more stable intermediate state "microscopic view with movement, number and speed of electrons" which can be seen to be fruitful in many explanation situations throughout the whole study. We want to give several examples of how this microscopic view is used by the students and at the end of this part we will describe the intermediate state "microscopic view with electrons" how we see it.

Example 1
The following part of transcript shows an engaged discussion immediately after the introduction of the microscopic idea by the teacher (H):

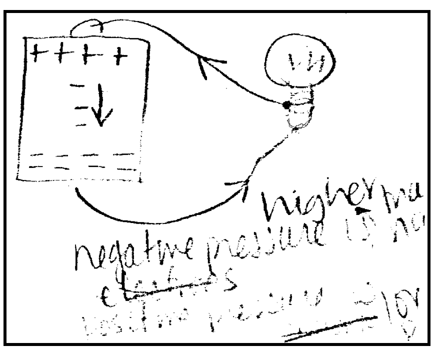
H: ... So, they push each other in this direction and here even, are less. If I draw (+) here, what does that mean?
G: It's, it's, oh! It's, (inaudible)...It's k...It's attracting them to the battery back.
H: Yes. Attracting.
C: And then they're getting (inaudible) to those.
L: And then they're just like, repelling off the electrons here.
C: And the extra ones will go down...
G: Oh, Yeah! Then it keeps just going, "Oh!", because..
L: It actually repels those away from..
G: Cause that couldn't even go down. (1;7)
H: So the battery. What does the battery do?
L: Organize! No! (Laugh)
G: Gets rid of...
C: Keeps them in order. (Laugh)
H: Yes, it gets them in order.
G: Yeah. It pushes it down.
H: It pushes electrons from here,
C: Oh! The extra go ...?
H: So it gets across here.
C: Down.
H: Works on...
C: It's like a machine.
H: Like a machine. Like a machine. Like a pump.
L: So it goes...The protons are like, repelling.
G: Wow.
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: Yes. Very nice.
C: Wow.
G: That's cool.

Students in this example use a lot of ideas related to electrons being attracted, being repelled, moving away, being pushed, and all this seems to them working "like a machine". To discussion is very spontaneous, the impression is that they like this view and it's very easy to them. Students grasp this idea and follow by adding new details to it.

Example 2
Following this introduction of electrons and their movement the idea of high and low pressure was introduced by the teacher, who tried to give a feeling of high and low pressure as a cause for movement. In their own writing and drawing after this combined introduction of microscopic view and pressure, the students show some attached meaning of pressure (like "electrons go from high pressure to low pressure", "negative equals high pressure"), but in their written texts they prefer the microscopic view with electrons.



L: The electrons are repelled from protons so they exit/pushed to bulb - make movement in bulb then are attracted back by the protons.
Electrons go from high pressure to low pressure.
the pairs coming in are equal so the extras go down



C: The battery works like a pump, pumping electrons out the bottom of the battery and receiving electrons in the top (positive) of the battery. The electrons are attracted to the protons and the extra ones go down to the bottom of the battery to be pumped out.
negative (:) pressure is higher than normal
positive (:) pressure is lower than normal

G: The battery has extra electrons that they push out into the bulb then the protons attract the electrons & then after they come together the electrons are pushed down the battery; pushed out again.

(High) pressure from battery to low press. light bulb, to (high) press. & (low) press. top of battery. ...

The last statement of G also shows that the pressure part of the writing sounds rather weird, like being memorized without meaning. It seems more related to a general idea of "loss of pressure" or "current consumption" than to causal thinking with pressure and pressure difference.

Example 3

At the beginning of the next session (session 2) the white board drawing (see above) was still there and the teacher asked whether it makes sense to them. C and G answered spontaneously. We give G's answer:

> *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.*

It shows students resonance with taking a microscopic view. This microscopic view was only explained once in the first session, not even with great emphasis. The statement "electrons move out through here into here" shows at the very opening of this statement the students main focus. The next part "because it's repelling out of here and it's getting attracted back to here" shows a tendency to a mechanical reasoning with electrons to come to an explanation. With "they create, um, energy" the old current1 concept comes into the mind again. But even energy is seen now with a microscopic mechanical view: "and...energy that moves it around to make it light up".

Example 4

The next example is from later in the course (session 4).

> *H: They all will become dimmer. And why? And now just explain why.*
> *L: Cause of the resistance that occurs. G: ...*
> *C: Cause...cause the movement of the electrons is...is being...impeded by the...*
> *H: Yeah. G: ...*
> *C: Slower, because there...there's five bulbs. (4;2)*
> *L: And it needs to be a rapid movement to make it light.*

"Movement of electrons" is "impeded" by the resistance, the electrons become "slower". This is a wonderful evidence of the power of the microscopic view because nothing of this kind was talked about this idea in this session before! The last sentence shows, that from this microscopic view comes a strong influence to change the meaning of "current".

Example 5

In a discussion about an interrupted circuit:

> *H: No current. That's true. But why is there no current? You say there is pressure and I agree with you.*
> *C: But there's nowhere to pull...There's no...the..*
> *L: There's no current because...*
> *G: There's no place to pull it back into the battery.*
> *H: Yeah. There is no pressure -*
> *C: There's no outlet.*
> *H: - difference. (4;7)*

Here we see little resonance with pressure or p-difference and more resonance with microscopic view: "nowhere to pull", "no place to pull", "no outlet".

Example 6

The following example shows two aspects of the use of "electrons" in session 4. First, again "electron" is their first thought explaining a battery. The spontaneous use of a microscopic view with electrons means the idea of electrons is powerful to them (electrons were not mentioned in this dialogue before). Second, the sequence of answers show that the term "electron" can be replaced by "pressure", as by current in other cases, thus again showing the basic "cluster concept current 1" being working. The battery statement in a worksheet in session 2 (segment 5) was: "A battery (cell) is a device that tends to maintain a constant electron pressure difference across its terminals." In addition, the dialogue shows the different intention of the teacher H:

> *H: What are the batteries doing? We learned that last time. What are the batteries really doing?*
> *C: The batteries are just providing the...*
> *H: What are they providing?*
> *G: The electrons.*
> *H: Yes.*
> *C: The pressure.*
> *H: Yes. They tend to maintain -*
> *C: High pressure.*
> *H: - a constant -*
> *C: A constant pressure.*
> *H: - pressure difference. ...*

The answers give especially strong support to the importance of the microscopic view for students as the answer H expected was more oriented towards pressure!

IS: microscopic view with electrons

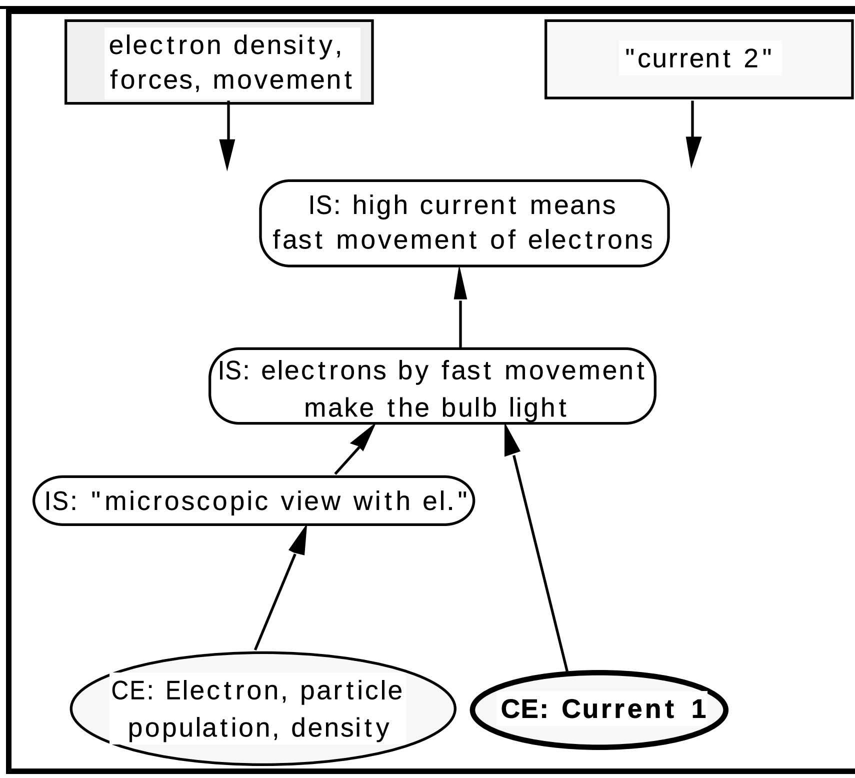
We have counted 54 records in session 1 to session 4 showing evidence for this spontaneous views of microscopic view of electrons by students. This, in our mind, is one hope for a better understanding of electric circuits. Nevertheless, this intermediate states from the point of view of physics has also some shortages.

We try now to specify students' meaning of this intermediate state. From the examples we can see that students have the following statements related to a microscopic view.
- Electrons can be pushed, pulled, attracted and repelled.
- This kind of forces are causes to their movement.
- These forces are related especially to the battery.

From a physics point of view this microscopic view still has some shortages:
- It is not connected to the concept "current".
- It is not or only weakly connected to pressure and pressure difference for voltage.

6.3.2 Changing the meaning of the concept "current"

At first we give an overview of the cognitive elements, the intermediate states and the teaching input in the following diagram:



Learning process with "current":
changing meaning and developing "intermediate states" (IS)
from prior cognitive elements (CE) and teaching input (TI)

At the bottom we have again the stable cognitive elements from pre-instructional influences. To the left the already described intermediate state "microscopic view with electron" is shown as it leads to a relation that electrons by movement makes the bulb light, and from that comes to an intermediate state. At the highest level the students develop an intermediate state in which the amount of current is related to the speed of electrons. We believe that this intermediate state has not yet a high stability in this learning process which means, in other words: It has not yet achieved a high status in the language of the conceptual change model (Hewson). This, in fact, means that the concept current has changed its meaning in a very important point.

Example 1

H: ... What do you think about current? And electron pressure in those circuits?
{Pause of about 6 seconds.}
L: I think there's a high current. ... L: I mean, I think it's going fast (inaudible) H: Fast.
L: Is that a term to describe current? I don't know. (2;4)

Example 2

C: ...currents from both batteries ...
L: ... bulb A is brighter because it is getting a direct current from battery 1 ... (4;1)

These example shows a use of "current" which we see as very close to "current 1", **current being an energetic fluid like fuel coming to the bulb and making some effect more related to its presence than to its speed.**

Example 3

H: ... What do you think about the ***current*** *here and the current here?*
G: It's not as high ***pressure*** *here (L pointing to B).*
In unison with L) and high pressure here (L pointing to A). (4;1)

"Current" is described by its "pressure".

Example 3

H: I think this is in contradiction to one sentence on these two pages. ...
L: There's the same amount of current everywhere. There's the same amount of current everywhere in here. It's the pressure and the resistance that are different. (4;2)

"Amount of current" is not clear in its meaning here (speed or fuel or energy), but I assume it is **not** related to speed and "current 2" here.

Example 4

L: The pressure makes the current. (4;2)

Here a differentiation between both concepts with a causal relation is constructed.

Example 5

L: So...the higher the current, the brighter the light. (4;2)

The meaning of "high current" is not yet clear, it might be related to speed already here (compare next example of L!), it also could mean a current with much power and big effects ("current 1").

Example 6

L: And it needs to be a rapid movement to make it light.(4;2)

Example 7

H: Now I make an experiment (shortening bulb A) and you explain it. What is happening now? C: ... G: ... C: ... H: What is happening now? Be careful.
G: Cause it...it's not losing the pressure, by going out through that other bulb.
C: ... H: And what about the movement? The speed?
G: It's, it's a lot faster L: It's faster. Less resistance C: ...
G: There's less resistance. So it's less passive. (4;2)

Example 8

C: More current means...How...You can't make more currents...if you...I mean...the batteries have their currents and you can't make any more or less if you're not changing batteries, correct? (4;2)

Battery as constant current source.

Example 8

L and G in session 5 after some discussion:

L: ... It is brightly lit because the pressure difference between f & g is big therefore the current is traveling faster causing more movement which means more light.
G: ... Pressure difference: bigger pd=brighter lite; vice versa. There is more of a pd in A. Because there is more current.

While L in this situation is expressing the correct physics idea, G is **not** mentioning speed and she uses the causal relation between pressure difference and current in the opposite order: because there is more current we get more pressure difference.

Example 9

H: ... What does the pressure do?

L: Well it makes the current either a high current or a low current.

L: It's the speed of the current that determines the pressure? (5;2)

"High current" is perhaps more related to the old meaning of "current 1". But in the following question L shows that she is aware of the relevance of speed. It is perhaps still the wrong causal order.

Example 10

G: Okay. I have another question, then. If this...Okay, if "a"...if pressure is what moves the current...(Ohm's p-prim, not p-difference) ...and there's high pressure here, here and here...then how come it doesn't move that current faster and make it a brighter light? (5;2)

G here is also very close to get the meaning of "current 2" and even in relation to pressure (not p-difference !), thus coming near to get Ohm's idea!

Example 11

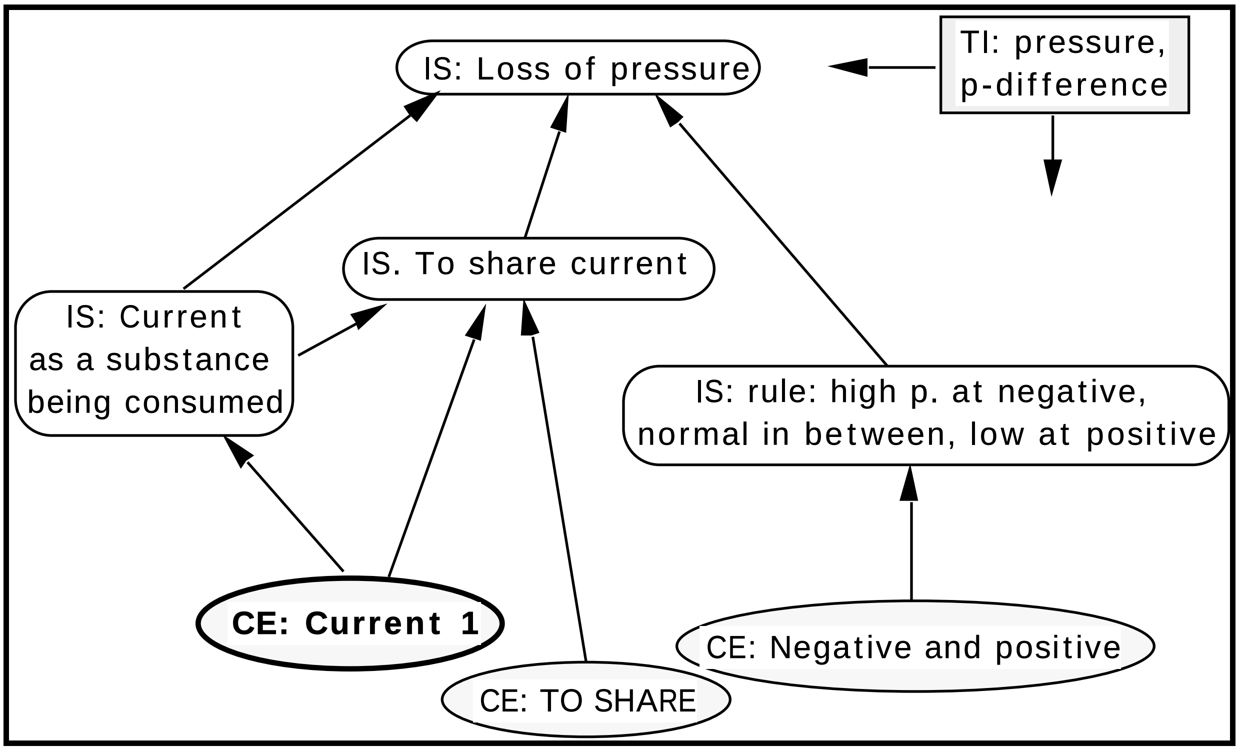
L (Written explanation): the current coming from battery 2 travels through a and is split between b and c. The pressure difference between b&d and c&e is low, so the bulbs are only dimly lit. The current is joined together again at f, therefore A is getting the whole current and is brightly lit. It is brightly lit because the pressure difference between f & g is big therefore the current is traveling faster causing more movement which means more light.

Example 12

L: The amount of current that goes through here. The, uh, the speed of the current. Is that, ***is that a correct term to use****? The speed of it? (6;1)*

6.3.4 Developing meaning for the new concept "pressure", given by instruction, and trying to make sense of it, related to old cognitive elements, old experiences, new experiences.

We start by giving an overview of cognitive elements, intermediate states, and teaching input in the following diagram:



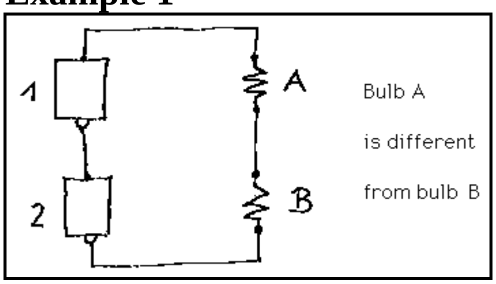
Learning process with "pressure": developing "intermediate states" (IS) from prior cognitive elements (CE) and teaching input (TI)

At the bottom you see the important stable cognitive elements from pre-instructional experience. We see two lines developing from this to an important intermediate state with pressure which we describe as the conception of "loss of pressure". This develops in two lines, one in developing the cognitive element "current 1", and the other using the teaching input about pressure and pressure difference together with some pre-knowledge about negative and positive to develop an intermediate state in which we see a rule used by students that high pressure is at the negative end of a battery, normal pressure is in between (for instance in the bulb), and low pressure is at the positive end of the battery. This rule, together with the current consumption sharing ideas, comes to an intermediate state "loss of pressure".

IS: High pressure at negative, normal in the bulb, low at positive as a rule.
This rule was given by the instruction, not as a major effort, but as a starting point for explaining pressure. It turned out that this **rule** played an important role in students' own reasoning with pressure.

IS: loss of pressure along the circuit
Students develop the idea of "loss of pressure" in different forms by applying the general cognitive concept "current 1" ("something is given from the source to the consumer") to the new word "pressure". Students have no specific meaning to "current", "pressure" or "energy", besides it is "something" which is given and consumed, e.g. to the bulb.
TI stresses the role of pressure difference as important cause for the movement and current (see e.g. 2;4 or 2;7a or 2;8). Students seem to see "loss of pressure" rather as a result of the current having done some work in the bulb. Both views again are similar with respect to talking about a pressure difference before and after a bulb, but they give totally different meaning to this difference.

Example 1



A circuit shown in the diagram was build up in front of the students, showing bulb A brighter than bulb B. Students were asked to give a written explanation:

*L: Bulb A is brighter because it is getting a direct current from battery 1. Bulb B is dimmer because the **pressure** leaving bulb A is low.*

This is the old "current 1" concept (giving "something" to make the bulb light), turned to "consumption" idea in the context of circuits and now **applied to the new word "pressure"**, tentatively, to find out its meaning.

Example 2
During a discussion of a misunderstanding between H and L:

L: Since they go from high pressure to low pressure. (2;4)

Example 3

L: But it's the pressure that makes the current. The pressure difference!
H: (In unison with L) Pressure difference.
L: Oh! If this is high up here, there is no pressure difference. That's why it's not getting bright! (5;2)

Example 4

L: I think so too. And I think knowing that...see, I was...all this time I was getting...the pressure...difference and the current...
G: Mixed up.
L: I was thinking they were kinda the same thing almost, or something. And it -
G: So was I.
L: And it's pressure is...the current depends on that pressure... (5;4)

7. Some final conclusions

7.1 Teaching and learning - some practical results

- Which of the teaching inputs had a comparatively high **resonance** in students' thinking and which had only a low resonance?
    - compare input with pressure difference and input with microscopic view
    - compare students use of pressure difference and microscopic view
- high resonance with **MICRO,** low with pressure and p-difference
- **there is a need for a conceptual change of "current", not only pressure.**

7.2 What do we mean by "learning"

- learning is applying old CEs to **"explore" new experience (!!)** and to "construct new meaning"
- learning is changing the meaning of concepts (e.g. current)
- learning is development of **new** cognitive elements /tools
- the result is an enriched repertoire of cognitive tools. Neither have the old ones vanished nor has nothing been changed and learned. There is a potential of old and new cognitive elements with a tendency to start in new situations with the familiar old ideas, but after some time or with small help the new elements are used also!

7.3 Other general aspects

The constructivist view of a cognitive system with some stable "cognitive elements" and actual constructions like "ideas" also implies a tendency to see many of the well-known research results about alternative frameworks **not** as cognitive elements but as results of construction processes using more general and more stable cognitive elements. As examples, we see "current consumption", "sink model of resistance" and "battery as a constant current source" as constructions using the pre instructional concept of current ("current 1") in special situations.

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