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A STUDY OF THINKING AND LEARNING IN ELECTRIC CIRCUITS

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1.Introduction

The authors have organized an International Workshop, "Research in Learning Physics: Theoretical Issues and Empirical Studies", March 1991 in Bremen. The principal idea of the workshop was to extend the very successful research tradition on student understanding to the investigation of learning processes. One of the results was to give high priority to investigations of "learning pathways" in all topics relevant for instruction. One important issue discussed in Bremen was the following question: What kind of cognitive entities are appropriate for describing learning processes? 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 in a learning process on electric circuits?

- Which knowledge representations in the field of electric circuits best can serve as a model, both to explain their thinking and to promote their learning?

- As a result of the learning process: What does the final state of students' cognitive systems look like? What kind of understanding and problem solving ability on the part of the students is reasonably to expect at the end of the learning process?

This research project represents the initial steps toward achieving the ultimate goal of describing the entire learning process.

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2. Methodology

Three college students were selected randomly from 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 directed at the students and the other directed either at the computer screen or the experimental apparatus. The study also had some aspects of a natural setting: the instruction occured 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. 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-videodisc software, 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 the elicitation of students own ideas.

The electron gas pressure model assumes electrons in a wire behave like a gas and that pressure and pressure difference become equated to potential and voltage. The central statement in this model is: the higher the (electron gas) pressure difference between the ends of an electrical device, the faster the electrons will move and the greater the current. A battery is assumed to provide a constant pressure difference across its terminals. The computer-video software[3] represents the electron gas pressure in a wire in terms of the *thickness* of the line appearing on the screen (see examples below).

The following page shows a general graphical representation of the instructional aim of this study describing a formal representation of the kind of cognitive system the students should develop.

[3] Developed with "Authorware" by Fred Goldberg and his group.

The aim of instruction was to arrive at a type of scientific thinking using a concept based on a relation between agent (voltage V), resistance (resistance R) and a result (current I). This will be called OHM's concept or OHM´s p-prim (diSessa 1990, p.12). So our aim was to teach for understanding this conceptual structure.

This includes that observables like brightness of a bulb or the geometry of the circuit or the voltage of the battery are also constructions inside the cognitive system.

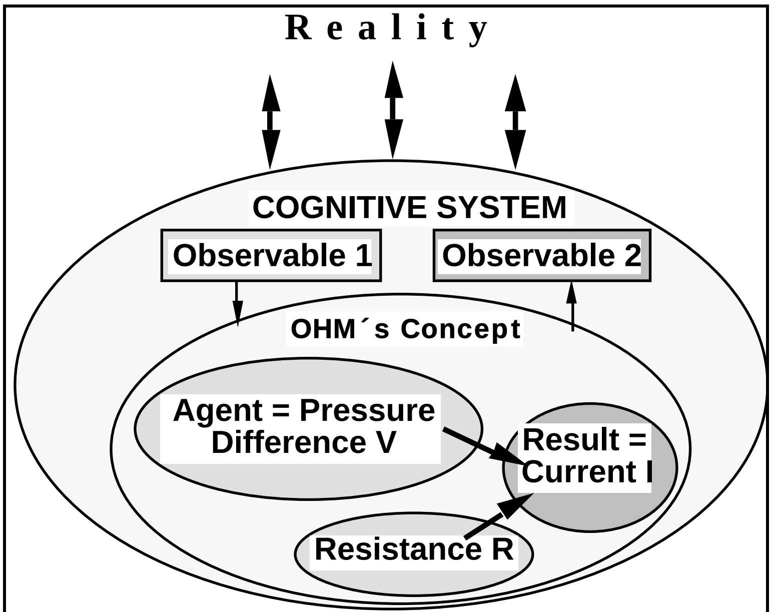


Fig. 1. Cognitive system aimed at.

The whole learning process was built up on hands-on activities, sometimes more and sometimes less open-ended. In addition there were computer-video activities, mainly focusing on predictions and on drawing "pressure diagrams" as a help for prediction and explanation.

The following pictures should give some idea of the whole teaching process. They show selected problems from the six sessions of two hours each.

Session 1:

Prior ideas of electric current, introduction of "pressure"

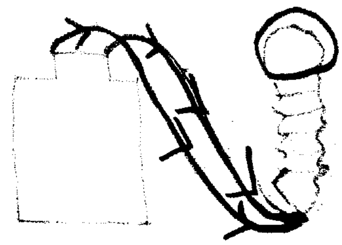


Fig. 2. Student´s idea.

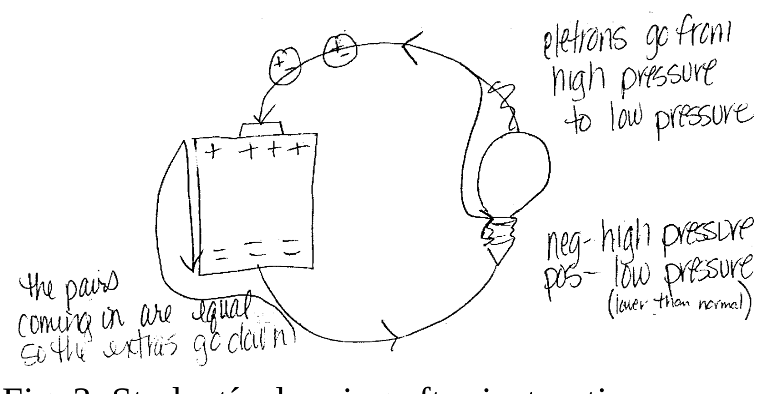


Fig. 3. Student´s drawing after instruction.

Students´ prior ideas were of the wellknown type: two currents go from the battery to the bulb. Their drawing after instruction seems to show some understanding of the idea of pressure. Lateron dialogues show that the meaning of "pressure" in many situations with predictions and explanations is closely related to "current" and "current consumption".

Session 2: Electron pressure in simple circuits

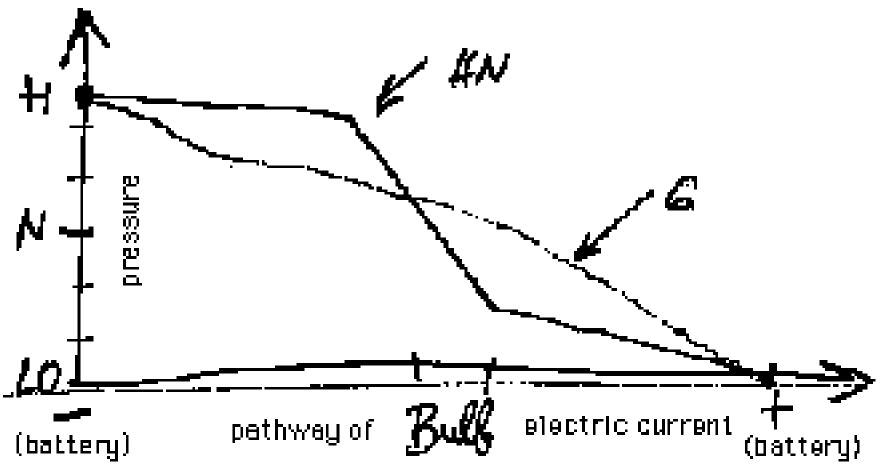


Fig. 4. Sketch done during the teaching process.

Fig. 4 shows a sketch of pressure along a simple circuit with one bulb, drawn from student G, with feedback from teacher (HN).

In a similar way pressure in a circuit with two bulbs in series was discussed afterwards (see below, point 5).

Computer-video: First "pressure diagrams" on the screen

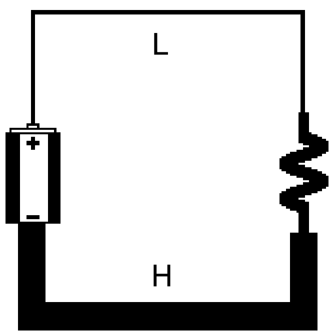


Fig. 5. Simple circuit

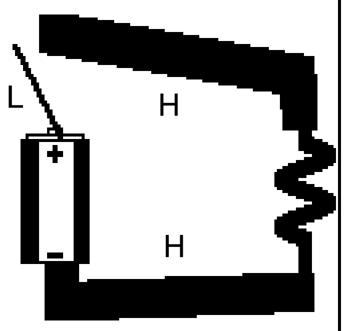


Fig. 6. Open circuit 1

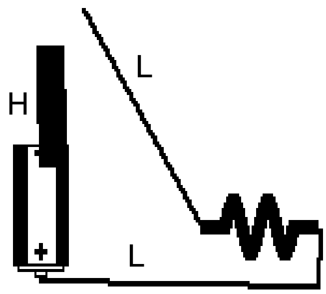


Fig. 7. Open circuit 2

(H = high pressure, L = low pressure, N = normal pressure.)

These first pressure diagrams showed that students had no problem to use this software and the symbols for high pressure (thick line) and for low pressure (thin line). But it also showed some difficulties: pressure at an open end of a wire was expected to be released. It was not easy to understand that pressure was constant throughout the same wire. But already in these first examples of pressure diagrams with computer it became evident that there is a great potential for interesting discussions and openended questions given with this software.

Session 3: Circuits with two batteries

Text and figure:

What does the steady current situation look like?

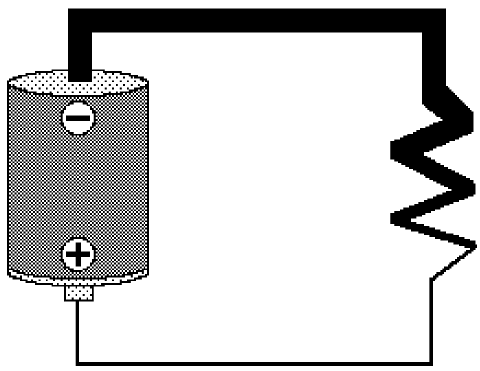


Fig. 8. General structure

This general structure was given in a text which was partly discussed during the session.

Open-ended lab: Find own circuits with 2 batteries and 2 bulbs!

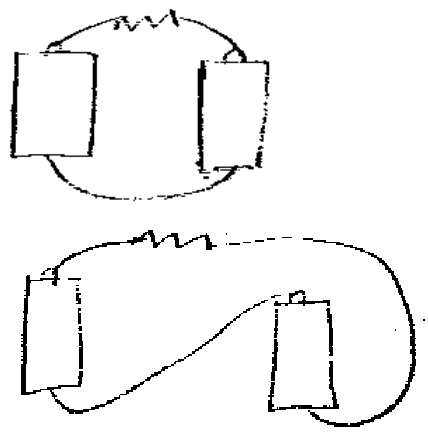


Fig. 9. Students´ own problems

These two circuits were found by students themselves.

Computer-Video: Modelling own circuits from Fig. 9.

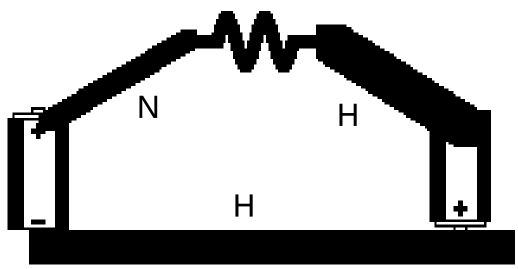


Fig. 10. First approach

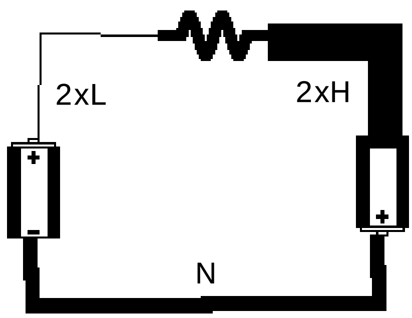


Fig. 11. Final result

Students started with "high" for the negative end of the battery and with "normal" for the point behind the bulb ("consumption idea") because of two batteries instead of one. During the process of discussion they always started with high or 2xhigh at the minus end of both batteries. So high pressure as a causal determination for the current to start was very important for them. The final idea of equal differences created by each of the two batteries had to be introduced by the teacher.

Session 4: Two batteries and two bulbs

Opening Challenge:
Two different bulbs in series.

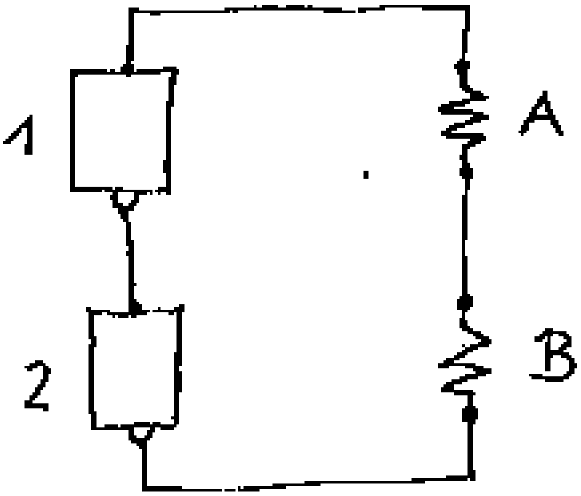


Fig. 12. Circuit diagram of hands-on experiment

Openended lab work: FIND A CIRCUIT WITH 2 BULBS AND 2 BATTERIES IN WHICH BOTH BULBS ARE AS BRIGHT AS POSSIBLE !

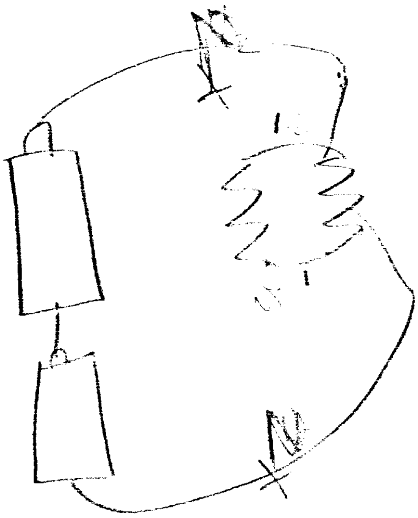


Fig. 13. Students´ solution.

Text: "Basic structure of electric circuits"

(1)	CURRENT ↗	VOLTAGE
(2)	CURRENT ↘	RESISTANCE

Computer-Video:
Two bulbs in parallel.

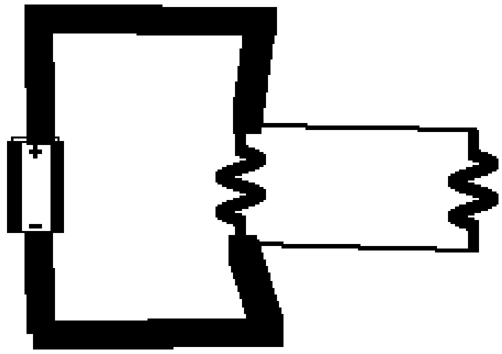


Fig. 14. First approach.

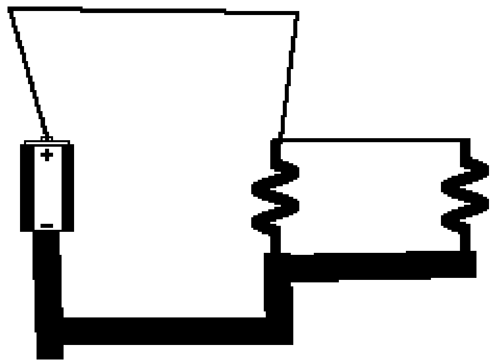


Fig. 15. Final pressure diagram

Session 5: Circuit with 2 batteries and 3 bulbs.

Tasks: Prediction, observation, explanation and "pressure diagram".
(2xH = double high, H = high, N = normal, L = low, 2xL = double low)

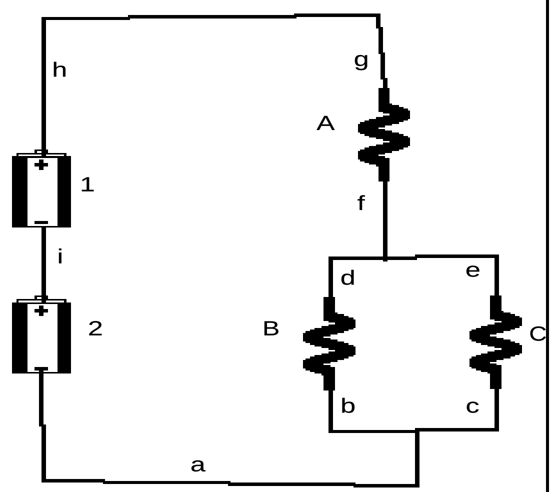


Fig. 16. Circuit diagram

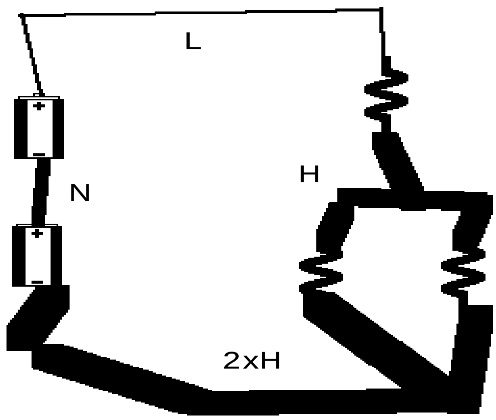


Fig. 17. First trial of students for a computer "pressure diagram"

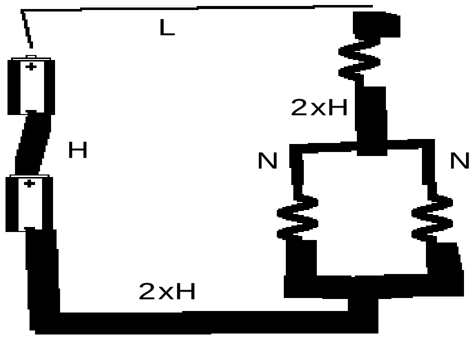


Fig. 18. Second trial of students for a computer "pressure diagram"

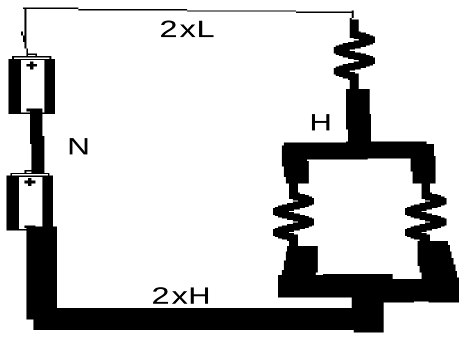


Fig. 19. Third trial of students for a computer "pressure diagram"

Session 6: Different Circuits (predictions, explanations)

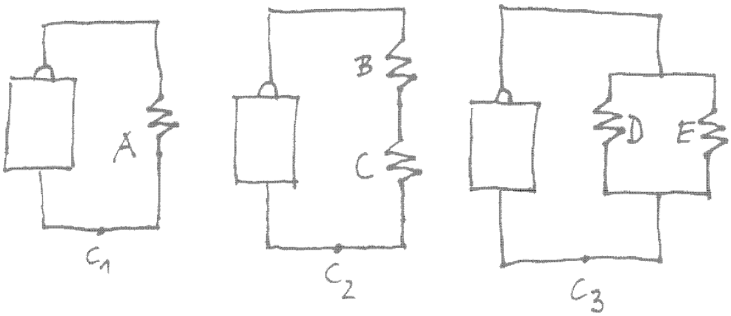


Fig. 20. Current in 3 whiteboard circuits

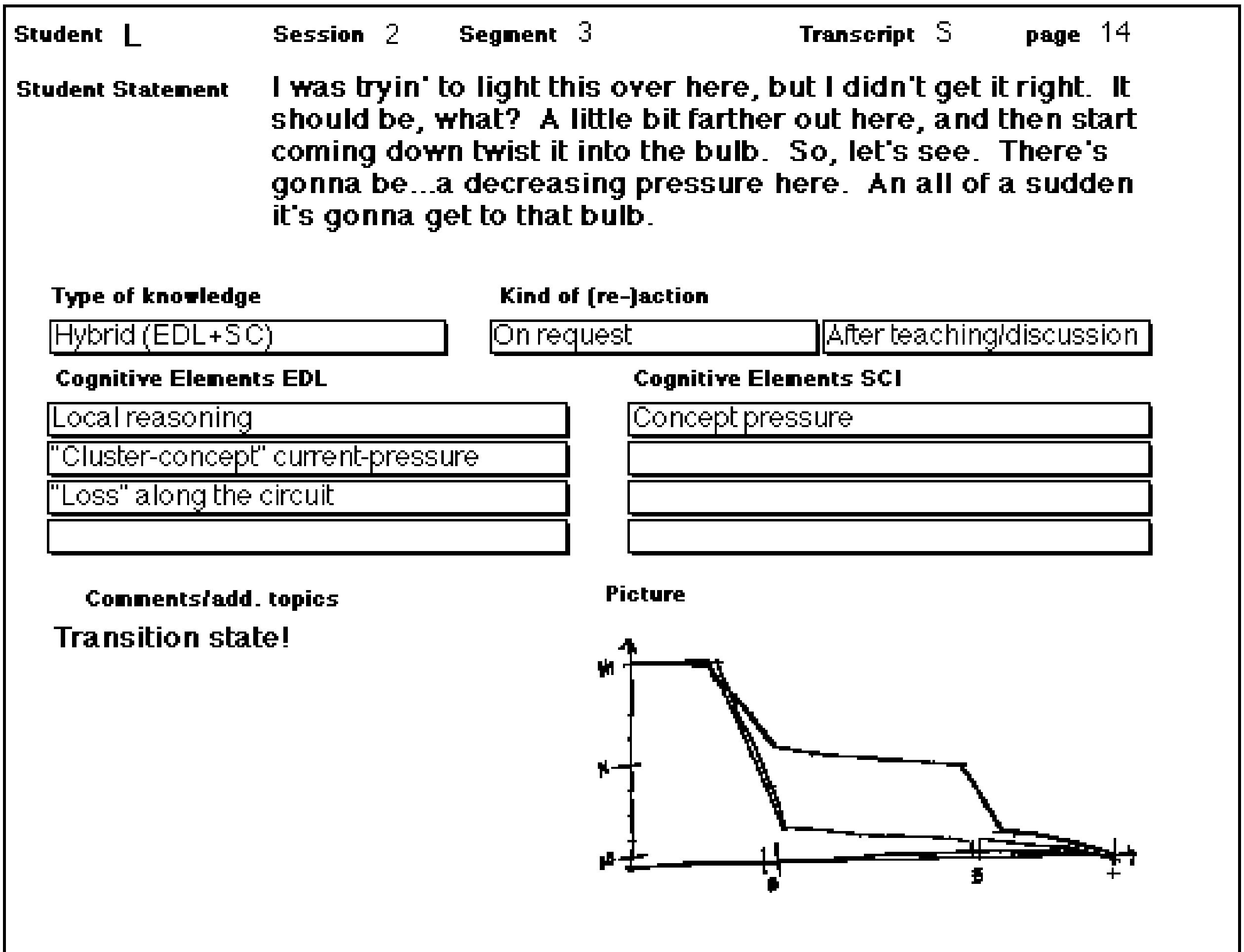
In addition hands-on experiments were carried out to determine the order of resistance of three different bulbs ("half quantitative"); additional pressure diagrams, etc.

4. Qualitative interpretive analysis

A qualitative database has been established to promote an iterative interpretation process. For all six sessions transcripts of video tapes were produced (about 500 pages). The software used to analyze these 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.Rhöneck 1985; v.Rhöneck 1986; Frederiksen and White 1991; Shipstone et.al. 1988; Heller 1990). They have been established as pop-up menue in FileMaker, which can be further developed and changed throughout the whole interpretation process.

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 record of the database, representing one student's statement and the cognitive elements assigned to it in an interpretive process:


Student L Session 2 Segment 3 Transcript S page 14

Student Statement: I was tryin' to light this over here, but I didn't get it right. It should be, what? A little bit farther out here, and then start coming down twist it into the bulb. So, let's see. There's gonna be...a decreasing pressure here. An all of a sudden it's gonna get to that bulb.

Type of knowledge: Hybrid (EDL+SC)

Kind of (re-)action: On request | After teaching/discussion

Cognitive Elements EDL: Local reasoning; "Cluster-concept" current-pressure; "Loss" along the circuit

Cognitive Elements SCI: Concept pressure

Comments/add. topics: Transition state!

Picture

Fig. 21. A FileMaker Record

By the iterative interpretive process described above we have arrived at the following **list of cognitive elements** (first research question), which seems to be quite powerfull for explaining students everyday life (EDL) type of thinking in electric circuits and their starting to use the science (SCI) type of thinking:

EveryDayLife (EDL)	**Science (SCI)**
I. Type of	**Committment**
- Different ideas in d. situations	- Consistency
- Confident (with wrong)	- "Wait a moment"
II. General Conceptual	**Framework**
- Local reasoning	- Circuit as a system ("steady state")
III. Schemes,	**p-prims**
- Consumption/GIVE - TAKE	- towards OHM's p-prim (A-R-R)
- S H A R E	
- S P L I T	
- The more ... the more	
IV. Conceptions,	**concepts**
- "Cluster-concept" current-pressure-energy	- "New" concept current
- Pushing,repelling	- Seperating current-pressure
- Pressure = pressure difference	- Concept pressure
	- Concept p-differences
- Easier/shorter route	- Concept resistance
- Resistance => brightness	

V.Special ideas

- Negative end of battery: Starting with
- Special role of "normal"
- Closed/broken circuit
- No place to go for current
- "Loss" along the circuit
- Following the path of circuit current

This list represents elements of a hypothetical cognitive system on electric circuits which is constructed to explain students thinking in this domain (see following page):

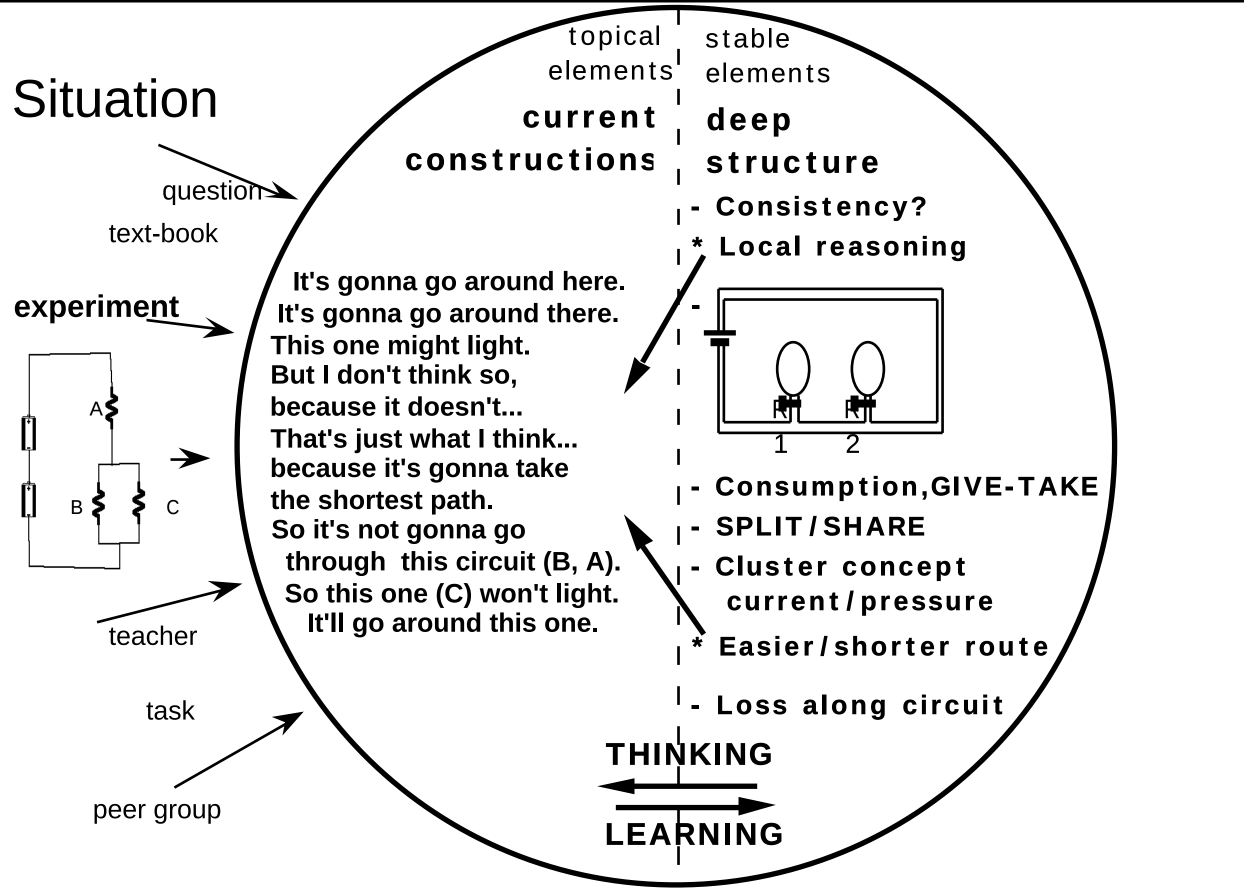


Fig. 22. Cognitive System "Electric Circuits"

The "cognitive system" (Niedderer,Schecker 1992) in general is a hypothetical construct of researchers. Its aim is to build up a net of theoretical elements which allow for a maximum of explanations of students´ behaviour with a minimum of assumtions. The cognitive system "electric circuit" is a hypothetical construct in the domain of electric circuits.

The following sketch models the conceptual framework of "local reasoning" which the students used preferably during the learning process:

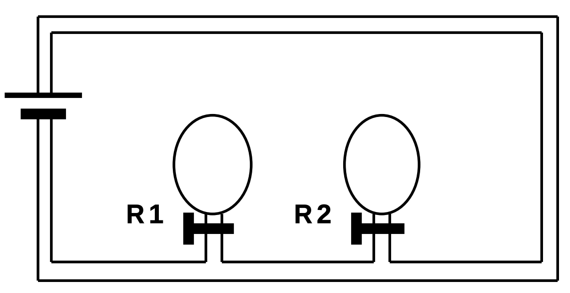


Fig. 23. Students´ model of resistance

It symbolizes students' thinking of the relation between resistance and current for each bulb **independently** in a series circuit**.**

A typical statement of a student: *"The dim 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 has more current flowing through it so it's creating a more...a more...a brighter. And this one...has more of a resistance, so the light is dimmer."*

Some of the other cognitive elements stated as hypotheses above will be demonstrated in the interpretive analysis of two dialogues shown below.

5. An example of qualitative analysis of thinking processes: Talking about current and pressure in a series circuit with two bulbs (session 2).

On the following pages we show an example of a dialogue together with an interpretation of thinking processes using the cognitive elements defined above. Students´ statements are in *Italics*, interpretations and explanations in standard letters, cognitive elements in **bold** letters.

The students are working on predictions and explanations of circuits with one bulb and a switch (written activity). Student G at the end of one task started to use battery and bulbs to build up a circuit. After a short time she adds a second bulb. All three students observe the brightness of both bulbs. Student L introduces an idea based on the cognitive element **to share**:

L: Its sharing the current -

H (teacher): 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 is coming through here, 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.

G is using "current" and "pressure" without differentiating them (**cluster concept current-pressure-energy**), and "lagging" has the meaning of **consumption**, an idea of this diffuse entity (like energy) being consumed ("lagging", "taken away") along the pathway and shared by the different bulbs.

C: Well, then why wouldn't one be lighter than...one be brighter than the other one? You know what I mean? It would seem...I mean...I, I agree with what you say.

L: ... I hooked it up just to that other wire, we would discover that this would.. .would be a right light. But since this is taking...pressure and electrons away from this...it's gonna dim this light. And then here they hasta go again and then the electrons'll be pulled away again. So each time...

H: What is taken away? G: What is taken away?

C: The pressure of the electrons. L: (In unison with __) The pressure.

H: So sharing the current. What does that mean?

L: 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.

The idea of "sharing" is related to features of the situation (two bulbs instead of one) and not meant to give a scientific model with generally and sharply defined concepts such as pressure or current in a physical meaning. Students use the concept "current" in a every-day life meaning (similar to energy) and so are far away from an OHM´s type of thinking, using pressure and current in a sharp causal link.

H: So one uses one half and the other uses the other half?

G: Not actually that much -

(In unison) (inaudible)

G: but...half of what it was supposed... what it used before.

In the following statement L starts some kind of causal reasoning. "Getting drained" seems to be the same idea as **consumtion.** L talks also about "movement" thus making a first step towards an OHM´s type of thinking. The meaning of **share** again is not totally clear: it could be the correct idea of same current in both bulbs, but it could also be near the idea of part of the current being consumed in each bulb.

L: I think what happens is that...This would be fine, but as soon as it gets to here, it's getting drained, cause it doesn't have enough...to light this (the second bulb). *So it's actually pulling from...It's pulling electrons...pulling...Yeah. It's pulling electrons from here. So there's not as much movement inside here which makes it a less light...because this one needs it. It's not so much...maybe that they share...it's just that...Like, when it leaves here, if we just...you know, ended it. It would seem like it was fine. But as soon as it hits this point and realizes that it hasta...have enough pressure to...light another bulb, it kinda drains from this one. Now it's doing nothing. Oh, it is, huh?*

G: I...turned it off. Oh! (Laugh) H: What do you mean by drains? ...

C: It takes. It takes pressure. It takes pressure from here and, and brings it to here to light this bulb. H: I see. Takes pressure from here. So...

C: LIke a water, you know, like water goes down a drain? H: Yes. A drain. ...

The discussion is now pushed even more towards "pressure" by the following suggestion of the teacher (H):

H: Would you like to draw a similar diagram like this? (see Fig. 4.)

C: With two bulbs, you mean? H: With two bulbs.

G: Lynn can be our designated drawer today. G: ... C: ...

G: No it's normal till it hits the bulb. And then it goes down over here, see how that is?

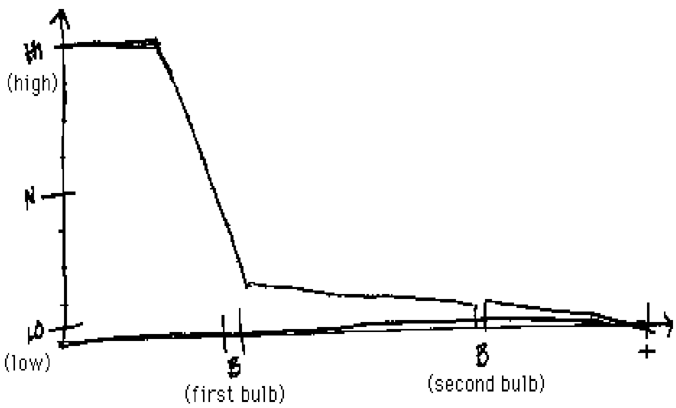


Fig. 24. L is drawing.

L: I was tryin' to light this over here, but I didn't get it right. It should be, what? A little bit farther out here, and then start coming down twist it into the bulb. So, let's see. There's gonna be...a decreasing pressure here. An all of a sudden it's gonna get to that bulb.

L: And it's gonna take -

C: lots more.

L: even more , so it's gonna...just keep...decreasing, I guess.

{Pause of about 13 seconds}

Students are now thinking about what happens to the second bulb. The students use **local reasoning** in connection with **sequential reasoning** to apply what they have learnt so far about loss of pressure in one bulb to the first bulb. The following process of students´own reasoning, especially L´s dramatic statements, consequently leads to the central question: But where does the current know from that there is a second bulb after the first one?

L: And then we'll...what...I...I know what I think, it's...hard to draw.

H: It's hard to. *G: How do you explain? H: (Laugh)*

L: But does that make sense, though? That, like...it's got this current. It's going just fine. Okay, this high pressure's coming out here. (**Negative end of battery: Starting with.** This also means a strong committment to causal reasoning.) *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. ...*

L: 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.

This statement clearly conecting some **consumption** idea with the new **concept pressure.** This example together with many others out of this study give strong support to the hypothesis of Frederiksen and White (1991) that causal understanding of electric circuits can be promoted with an "aggregate flow model", which makes a connection between students' strong tendency to use **local reasoning** and a causal model based on an OHM's type of thinking. It can perhaps help students to understand why there is a constant current in every series circuit instead of only postulating it. (See Fig. 26 below.)

Meanwhile a second student (C) had drawn a diagram by her own.

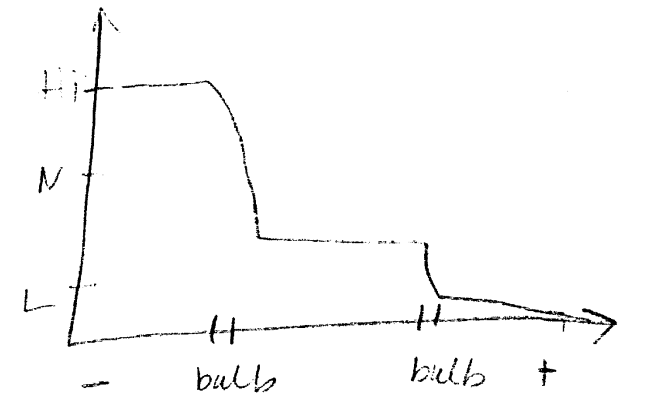


Fig. 25. Drawing of C (independent!)

H: ... Yeah. That's similar! Did you do that before? Oh, I didn't see that! Aha! Sorry!

C: Is that, I mean...that's what -

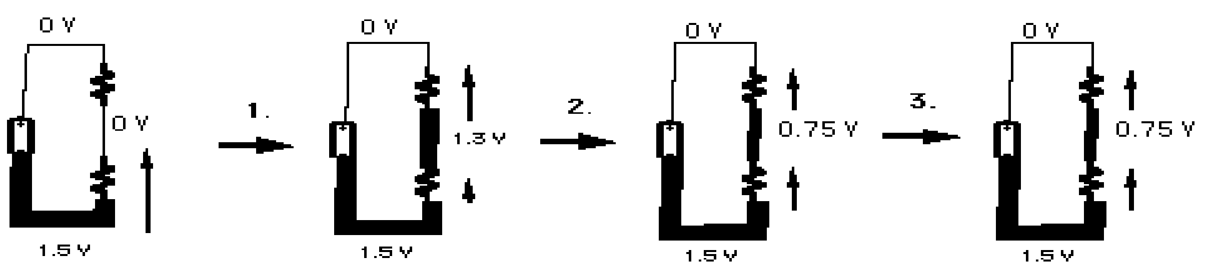
H: It's near to what I think ...

H: What is the difference, now? How does this perhaps explain?

G: Cause it's not taking it -

L: The pressure (inaudible)

G: Cause it's not taking as much. ***But why doesn't it?***
H: Why doesn't it? That's a good question! That's a really good question! It doesn't take the whole pressure.
G: Yeah. Why doesn't it, though? H: Why doesn't it though?
L: How does it know it's gonna need more?
H: Where does it know from? Where does it know from? That'a a good question. {Pause about 7 seconds.)
The teacher uses a similar diagram as C´s. He starts with the assumption of pressure like in L´s drawing and uses the causal link between pressure difference and current to argue:
H: Well, let's assume like this. Then a lot of current would come here. (Pointing to the point between the bulbs.) A lot. Because a big pressure difference makes a big current. A lot of current would come here. ... So, the pressure would go up here (Pointing to the point between the bulbs.) .



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ig. 26. From transition state to steady state with pressure diagrams

The pressure would by this procedure change until the currents in the first and second bulb become the same. The "transition state" of current and pressure would change to the stationary state of a series circuit with constant current. So the current does not need "to know" before, the stationary state can be seen to be realized (very fast) afterwards.

6. Analyzing a dialogue at the end of the learning process

In general, the learning process is analyzed as a process of the cognitive system using "old" cognitive elements to make sense of "new" situations. That is what we call THINKING, while changes of cognitive elements in the course of thinking are called LEARNING.

A circuit with three bulbs and two batteries (not yet connected at one point) is shown as a real experiment to the students, without circuit diagram at the beginning. [4]

(1) First phase: Starting with every day life type of thinking (EDL).

H: Now today I want to start with a challenge. Look at this circuit. It has three bulbs. They are equal this time. They are all the same bulbs. And you should think about prediction what will happen if I close the circuit here.

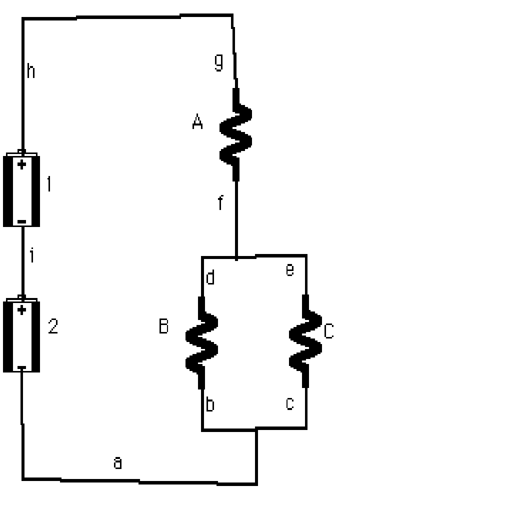

Fig. 27. Diagram of hands-on circuit

>>>>>>>>>>>>

Students start reasoning about predictions in a new situation by using old cognitive elements of the EDL group. L uses **local reasoning** in connection with **following the path of circuit current.** The route 2-a-B-A in the real circuit build up on the table in front of the students looks shorter, L is using a cognitive element **easier route:**

L: Well, let's think about this. This one goes through this way. And it gets to here. I think it'll take this path (she is pointing to B and A)*instead of going through here* (C). *It'll take this path and so it'll have to go through here. That bulb will definitely light* (pointing to B). *That bulb will definitely light* (pointing to A).

G: Yeah.

L: When it gets to here **?**, *I don't think it's gonna come...back through this* **?***way. I think it'll go through this one here. -*

G: Unless it gonna...unless the faster path (=shorter path) they choose is just this, and then these two (A and B) *will light. And this one wouldn't.*

H: So. Tell me again. G: We think that - H: What is your result.

The first phase ends with a first prediction: B and A will light, C will not light.

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[4] ">>>>>>>>>>>>" indicates cuts in the dialogue, protocol statements are in *Italics*, interpretations in normal letters, cognitive elements in **bold** letters.

(2) Second phase: Students start to use scientific concepts by their own ("resistance"), only one at first, often with a meaning related to EDL (e.g. same resistance means same brightness).

G: We think that it's either gonna...No wait! But the resistances are all the same, though. C: Yeah, that's right...

G: So I think all of them will light. H: All of them will light.

C: ... H: ... C: ... G: I said all...will.

The second phase ends with a second prediction: A, B and C all will light.

(3) Third phase: Scientific concepts from teacher are used by students.

H: ... What do you think about current in all those wires? About the amount of current.

This question of the teacher is in resonance with **local reasoning.** The question was about "current", the answer *high* sounds like "pressure", thus showing a tendency towards **cluster concept current-pressure.**

C: Well, it's high when it comes out. In"a." H: In "a" it's high. Yes.

G: Okay, now...if...okay, if...if, by chance...it's, okay...it's high here. It splits up here, okay? And then it's getting used right here, right?

H: Yeah. G: Is it? H: It's getting used in bulb "C" you're saying?

G: And "B" H: And "B"G: Is that right?

H: No. (Laugh)

(4) Fourth phase: Feedback from teacher starts own scientific thinking of students

A very interesting part of the dialogue is started with this NO.

G: Okay. Well then I...that's what...that's what I've, so far, from being here, have understood. C: Yeah.

G: That that was what happens. When it goes through here. It goes through here and it takes up some of the current and that's not right.

This statement seems to show that students have learnt something definitely wrong during the instruction. But if we take for granted that cognitive elements like **cluster concept current-pressure** are very stable, it is clear that students may have related every statement about pressure also to current thus having an explanation to this student´s confusion. And the next statements show, that this simple NO "clicks" them to the correct reasoning.

H: Not right. No.

G: But it takes up some of the pressure. H: Yes. G: That's right. H: ...

G: The current remains the same.

C: The current pressure is released?

G:So that's why. Because the current just keeps on going. It's two times here. It's split up one time. One time. And then up here. And then goes back here, back to two current.

H: Yes. So what would you say about the amount of current in a, b, c, d, e, f, g, h, i?

G: It's all the same. Well, so then it's two times here. One time. One time. Two times. Two times. Two times.

It seems like G is able to give a correct explanation in terms of the scientific concept current.

>>>>>

(5) Fifth phase: Own scientific thinking

L is giving spontaneous support to the hypothesis of a **cluster concept current-pressure:**

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.

H: Yes. Ummm.

G: Pressure. Now pressure comes out -

L: From the bulb.

G: And there's high pressure coming out. (**Negative end of battery: Starting with**) *Coming out. Coming out. Going in here. And then that has to split. The pressure has to split?*

Now again students show difficulties to grasp the idea of constant pressure throughout a wire (good conductor). After some help from the teacher, the discussion comes back to pressure and current:

L: Pressure doesn't lessen.

L is referring to a cognitive element **"loss" along the circuit.**
G: So, just to jump ahead a little bit. It's not pressure that makes the light brighter or dimmer. It's the -

G+L: The current.H: It's current. Yes.

G: So what does the pressure do?

Students themself at this level try to change the every day life **cluster concept current-pressure-enrgy** and differentiate between current and pressure.

H: Okay. I give this question back to you. It's a good question, but I think that you should be able to talk about it. What does the pressure do?

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

In this answer "high current" can have different meanings: it can mean a big amount of current in the scientific meaning, but it also could again be some sort of **cluster concept current-pressure**, taking high from pressure.)

C: It makes it travel. I mean, it's gonna go from high pressure to low pressure. And low pressure to high pressure. It travels. That gives it direction.

L: It's the speed of the current that determines the pressure?

H: The speed of the current, the amount of current is the same as the speed of the current.

These statements clearly indicate an OHM's concept as it was aimed at: pressure "makes it travel", "it gives it a direction", "the speed of the current" is determined by the pressure.

7. What does the final state of learning look like?

The following summarizing conclusions are drawn from observing these three students´ understanding in *new* situations or problems which cannot be solved with only applying memorized facts.

A first question could be: Was there a conceptual change to be observed? By "conceptual change" we mean the development of clearly distinguished scientific concepts, either by replacing the old every day life concepts or by having a coexistance with clearly separated meanings of concepts or by upgrading scientific concepts. We think that no conceptual change of this type was observable in this study. We doubt, whether it can realistically be expected from these students with their special vocational perspective (primary school teachers), in a short period of three weeks. This situation might change dramatically once these students start to teach this subject themselves.

Instead of "conceptual change", what is likely to be the result of learning (*final state*) can be described as *"knowing about"* : the cognitive system has been enriched with a first idea of "new" science concepts "current", "pressure difference" and "resistance"; the conceptual ecology has to be readjusted, perhaps over years, depending on the function of this knowledge in the life situation of the student.

In the final state of learning at the end of this learning process OHM's concept with the structure

AGENT = Pressure Difference/Voltage(V)

Resistance = Resistance(R)

Result = Current(I)

can be activated for understanding and problem solving with the following *limitations:*

- Getting started with a new problem is generally done with "old" everyday life type of thinking. This result could be seen as disappointing. But discussions with physicists have given evidence to the hypothesis that this statement is true even for experts.

- The science concepts are used in new problems only after some every day life type of thinking and/or with some help (having seen the experimental result first, getting some hints from an "expert"). Correspondingly, experts sometimes report, that to use scientific concepts in a *new* problem by themselves often is done only after some explicit controll or not being successful with an every day life approach.

- The meaning of science concepts is constructed generally by using "old" cognitive tools from everyday life type of thinking, e.g. thinking in the frame of local reasoning, attaching the old current consumption notion to the drop of pressure, resistance with local meaning, tendency to mix up pressure, p-difference and current (as in the old "cluster concept").

- The full complexity of an OHM´s concept, making relations between all three scientific concepts and to observable facts has not been achieved by these students.

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