AN INDIVIDUAL STUDENT'S LEARNING PROCESS

IN ELECTRIC CIRCUITS

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Paper presented at NARST Annual Meeting 1994 in Anaheim, CA
An Individual Student's Learning Process
in Electric Circuits

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1. Introduction

1.1 Objectives of the study

In March 1991, the authors organized an International Workshop "Research in Learning Physics: Theoretical Issues and Empirical Studies" in Bremen, Germany (Duit, Goldberg, Niedderer 1992). The principal idea of the workshop was to extend the very successful research tradition on students' preconceptions to the investigation of learning processes. One of the results was to give a high priority to investigations of "learning pathways" in all topics relevant for instruction.
The **research question** of the present study relates to this issue in the domain of electric circuits:

- How can a learning process of a single student be described which took place during an instruction of six sessions (90 minutes each)?

This is both a question of methods and results in this special topic area.

In doing this we use the following theoretical assertions:
- Students start with many prior conceptions or preconcepts from their everyday life experiences (e.g. an everyday life view of "current")
- During the process of instruction students form new "intermediate conceptions", built from their prior conceptions in interplay with new experiences (experiments) and the contents of instruction. These are different from prior and from scientific conceptions and gain some stability as kind of stepping stones of the learning process.
- A learning process can be described by finding those "metastable" intermediate conceptions, describing when and how they develop and are used by a single student, thus describing conceptual change in relation to aims and content of instruction.

In analyzing this process in detail we come to empirically based hypotheses about impacts of special elements of instruction on the learning process.

1.2 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 aimed at the students and the other aimed either at the computer screen or the experimental apparatus. 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 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.

1.3 Instruction

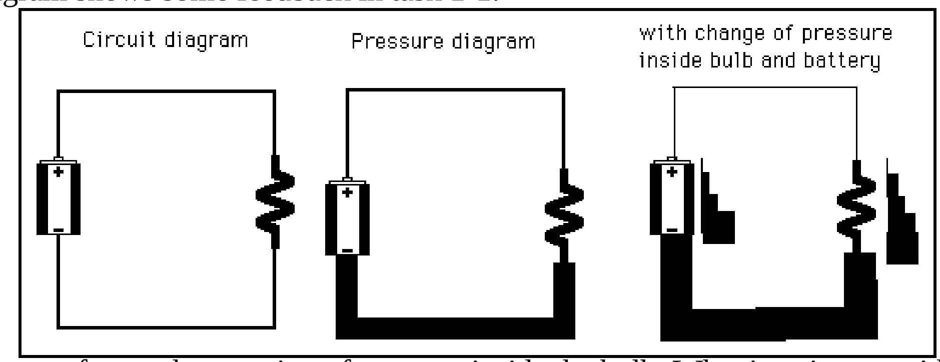
The *instructional process* was guided by the following major ideas:
- Use of open-ended hands-on experiments with batteries and bulbs.
- Teaching electric circuits with an electron gas pressure model.
- Use of a computer-videodisk software program, which provided a tool for representing students' own 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.

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 greater 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 be ideal and does provide a constant pressure difference across its terminals. The computer-video software program represents the electron gas pressure in a wire in terms of the *thickness* of the line appearing on the screen (see example below).

Some of the starting teaching activities were:

- Experiments with battery and bulb:
- General rule to make a bulb light
- Introducing a microscopic view of electric current
- Introduction of pressure
- First pressure models with Computer

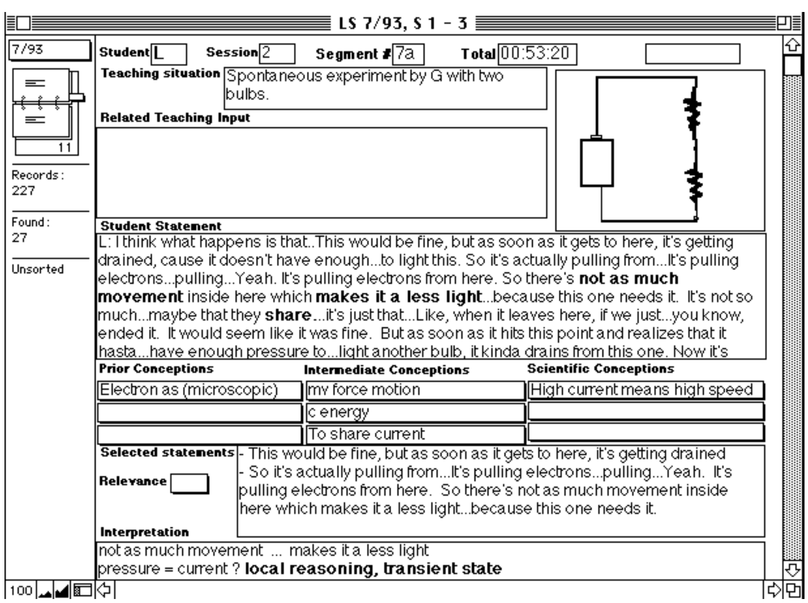
The computer-video software was explored by trial and error and little additional explanation. The following diagram shows some feedback in task 1-1:



The last diagram refers to the question of pressure inside the bulb: What is going on with the pressure inside the bulb?

1.4 Qualitative interpretive analysis

A qualitative database has been established to promote an iterative interpretation process [3]. The powerful software used to analyze the data was FileMaker by Claris. Hypotheses of cognitive elements like "prior conceptions" and "intermediate conceptions" have been defined on the basis of the previous research results of many other researchers (Niedderer, Goldberg 1993).



[3] First version of transcripts (about 400 pages) was done by Joy Massa, San Diego

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 with selected pieces of data giving evidence and/or counter evidence, and using these cognitive elements to analyze and describe the learning process of a single student..
The previous picture shows one record (out of about 400) of the database, representing one student's statement and the cognitive elements assigned to it in an interpretive process.

2. Basic view of learning processes

Learning is seen as a change in cognitive structure of students. Related to research traditions in physics education (e.g. "cognitive structure and conceptual change", West, Pines 1985) the most interesting cognitive elements of this cognitive structure are described as students' conceptions. The described cognitive elements are constructions of the researcher; their validity is tested by their usefulness for other researchers and for teachers.
Conceptions are used to describe learning processes in the following way:

- "Prior conceptions (PC)" are cognitive elements which were developed before teaching.
- "Intermediate conceptions (IC)" are conceptions developed during the teaching-learning process, often being still different from scientific conceptions. These intermediate conceptions are taken into account only if they turn out to be somewhat stable, e.g. more stable than spontaneous ideas only used once.
- "Scientific conceptions (SC)", held by the teacher (a physicist), describing the aim of teaching.

All these conceptions are described by smaller "pieces of knowledge" for reasoning that students seem to be applying in problem situations. We are calling these pieces 'facets' [4]: "A facet is a convenient unit of thought, a piece of knowledge or a strategy, seemingly used by the student in addressing a particular situation." (Minstrell 1992, p. 112) So every conception is described by facets.
The prior conceptions are important for learning in (at least) two ways:

- students tend to use them instead of scientific conceptions during and after teaching
- the development (construction) of new intermediate conceptions is build upon these prior conceptions.

In addition the learning process is analyzed in terms of interrelation between cognitive structure of students and the instructional process. For this analysis we use the "teaching input (TI)" as elements of instructional information related to the development of cognitive structures.
So the entire learning process is described by two types of processes:

- developing new intermediate conceptions
- changing prior or intermediate conceptions by adding or changing single facets

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 prior and intermediate conceptions. "A key factor in the learning process is the status (Hewson 1981) that new and existing conceptions have for the learner". Our observation is that students who already learned the scientific concepts for eight hours, while explaining a new experiment again start with the prior conceptions, but after some time and discussions with only little interference of the teacher try to start to use the newly developed intermediate conceptions (Niedderer, Goldberg 1992). 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.

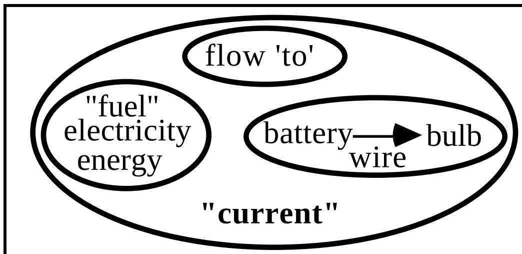
[4] The idea to use facets in this way as parts to describe conceptions was developed during a discussion with Igal Galili in Bremen, Oct. 1993.

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 conceptions.
Brown and Clement (1992) speak of "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 "EDL-current". 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 "EDL-current" concept (see below) 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.

3. General cognitive starting point of all students: Prior conception "everyday life current"

The prior ideas of students about "current" are well known from research in physics education. We gave a review of the results in Niedderer, Goldberg (1992). We give a very short abstract of the main result about students' prior conception "current" here.

The conception "EDL-current" then can be described by the following facets:
- "electricity": substance like fuel, energy
- "movement" (flow 'to', flow 'through'), and
- from battery through wires to the bulb



Cluster concept “EDL-current"

This conception 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.
A complete comparison between all facets of this prior conception, the facets of a newly developed intermediate conception "microscopic view of current", and facets of the scientific conception is given in table in 4.1.3.

4. Learning Process of Student Lynn

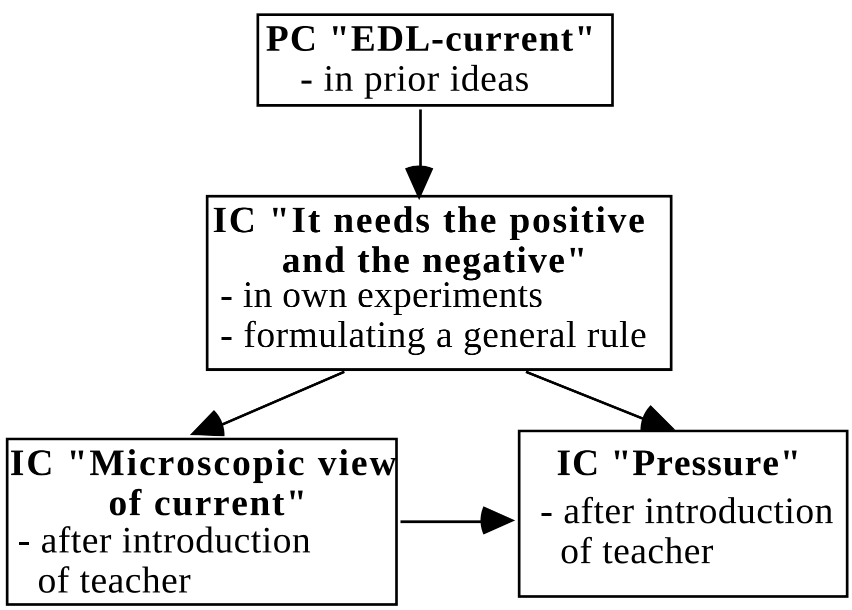
(Cognitive Development/Learning Pathway)

During the following paragraphs a series of selected "learning steps" is described always in the same manner. In "general description" the relevant (new) cognitive element (conception) is described briefly. In "teaching activity" an overview of the instructional situation is given. Then "qualitative analysis of transcript" contains a detailed discussion of the cognitive development. In "use of this prior conception throughout the learning process" we give selected examples of later situations in which this conception plays a mayor role in the teaching-learning-process.

Overview of the learning process of Lynn:

- In session 1 Lynn is showing the prior conception "everyday life current", developing a new intermediate conception "it needs the positive and the negative" and starting to develop two new intermediate conceptions "microscopic view of current" and "pressure".
- In session 2 the new intermediate conceptions "microscopic view" and "pressure" are developed in several applications always with a bias of the prior conception of "everyday life current".
- In session 3 a new intermediate conception "resistance" is developed; the former intermediate conceptions are applied and enriched with more facets, and the intermediate conception "pressure" is enriched by aspects of "pressure difference".
- In session 4 these intermediate conceptions are further developed and the facet "Ohm's causal relation" is especially developed.
- In sessions 5 and 6 and in the final exam no new intermediate conceptions are discovered; the old ones are differentiated but some of their shortages still remain.

The following diagram shows an overview of Lynn's cognitive development in sessions 1 and 2:

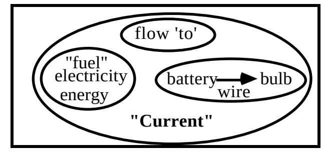


Learning pathway of Lynn
in session 1 and 2

4.1 Development of Lynn's main intermediate conceptions in sessions 1 and 2

4.1.1 Prior conception "EDL-Current" of Lynn

General description



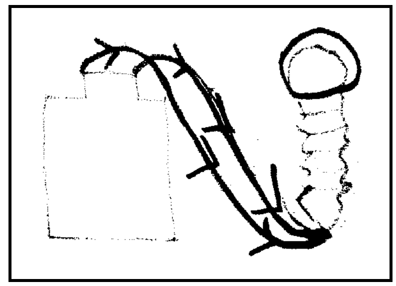
Lynn uses the conception "everyday-life current" ("EDL-current") during the starting teaching activity.

Teaching activity

A questionnaire “Your Prior Ideas about Electricity” is given to the students.

Qualitative analysis of transcript [5]

Lynn’s answer looks as follows:



> *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.*

Lynn is using all facets of the prior concept “EDL-current” as stated above: “flow/move from -through- to" and "battery - wire - bottom of the bulb" and the synonymous terms "electricity/power", "electrical currents" and "materials". (All students draw two wires from one battery point to one bulb point.)

Lynn uses also a second idea: "Perhaps one wire is negative and one positive like the cables when you jump a car battery", which is not in contradiction to current being seen as an energetic stuff given to the bulb to create the light. Lynn follows this idea throughout the whole session (consistency !), it is a fruitful starting point for her to follow the discussion about “current” (see 4.1.2).

Use of this prior conception throughout the learning process

Lynn is developing new and better (intermediate) conceptions in all sessions. But she is using this prior conception in new and complex situations throughout the whole process, often as a starting point and often in connection to new words like pressure or electron.
In session 2 when discussing two bulbs in series:

> *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. 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.*
> *(inaudible)*
> *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.*

In the first sentence Lynn is using the words current, pressure and power all in the same meaning! In the second sentence even the number of electrons is used. All of them have the same meaning of fuel bringing energy to the first bulb and after the first bulb having no more or not enough of it. This is the same in the following statement which was made in the same situation:

> *L: ... But since this* (the first bulb) *is taking...pressure and electrons away from this ...it's gonna dim this light* (the second bulb).
> *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.*

[5] In all parts of transcripts L stands for Lynn, H for the teacher and C and G for the two other students

So, again here more current means more fuel with energy. So something energetic is consumed, either current and/or pressure and/or electrons.

In session 3 a circuit with two batteries in series and one bulb is discussed. Her first written hypothesis contains the following sentence:

L: The light is brighter than usual because it is getting currents from both batteries.

When Lynn tries to understand the result of the computer pressure model(2xhigh pressure before and 2xlow pressure after the bulb) she is reasoning as follows:

L: We think that if there's this much pressure going in, it's gonna make this light really bright and it's gonna use so much that's it's gonna come out really low.

In this case "pressure consumption" is derived from "current consumption", which from an energetic view for Lynn means the same. In this case this is a positive step to apply the pressure concept (drop of pressure while passing a resistor) in a scientific way.

In sessions 4 and 5 there are still many hints that students have difficulties to separate the current concept into two scientific concepts current and voltage (pressure difference). Especially the idea that pressure is split between two bulbs which are parallel is coming back is Lynn's reasoning in session 5 and in the final exam "electricity".

4.1.2: First intermediate conception of Lynn: "It needs the positive and the negative."

General description

During the following teaching activities Lynn develops a new intermediate conception: "A proper electric circuit needs the positive and the negative."

Teaching activity

In session 1 after the questionnaire the following tasks were given:

#2: HOW CAN YOU MAKE A LIGHT BULB LIGHT?
#3: GENERAL RULE TO MAKE A BULB LIGHT
#4: TOUCHING POINTS OF CELL AND BULB

2 was an open ended lab where the students tried to make a light bulb light, in # 3 the task was to discuss and write down a general rule; # 4 again was open ended lab.
These tasks and the feedback they gave from successful experiments worked as a very effective teaching input. This activities are clearly to be seen as the first **"big success"** with electricity (see Lynn's statement in "additional comments", below).

Qualitative analysis of transcript:
Lynn's development of the intermediate conception “it needs both positive and negative”

At first, right at the beginning Lynn uses a first idea of this kind spontaneously in her written explanation in the questionnaire “Your Prior Ideas about Electricity”:

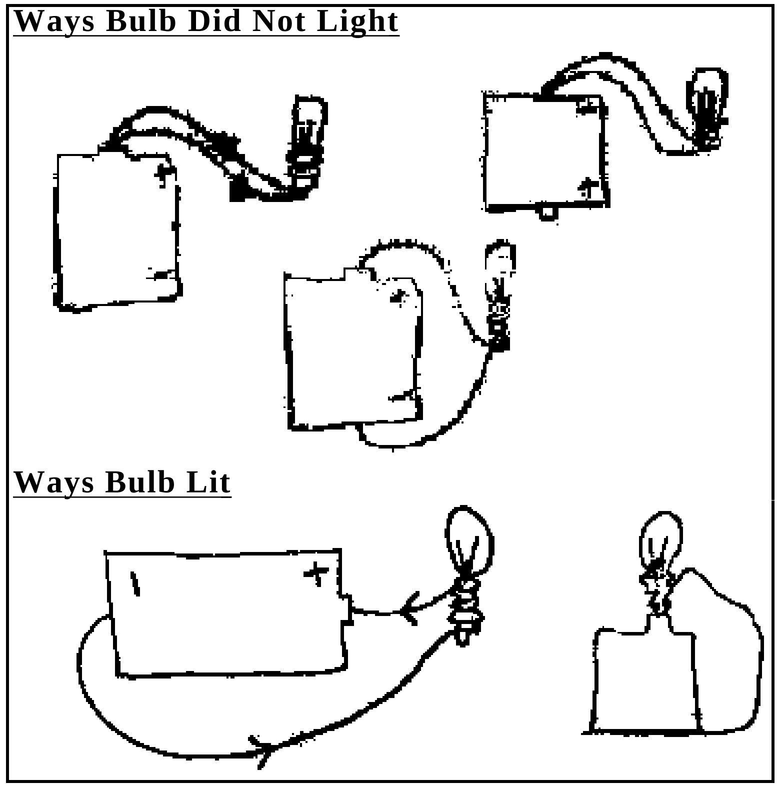
L: Perhaps one wire is neg and one positive like the cables when you jump a car battery.

In her additional verbal explanation she already talks of “currents from positive & negative ends of the battery”:

L: ... It made me think of jumping a car. You know, how you have a like, a positive and a negative? I thought, like, one wire was like, positive. And one was negative. You know, how you have two different colored wires, like the battery or whatever? So I thought that they both went the same direction. And that the difference between the two. Why there needed to be two was because one's positive and one is negative. ... You need currents from positive & negative ends of the battery. Positive & negative at cell base & metal.

During the teaching activity #2 Lynn together with the other students tried hard to find a way to make a light bulb light. Lynn's drawings done afterwards looked like this:

These drawings illustrate her struggle very well and help to understand her feeling of success afterwards.
During the next activity (#3, task 2. on the sheet) Lynn comes to a modification of her prior conception of current by building on her first idea about positive and negative “wires”, now using “charges” - which was a topic in the physics class two weeks ago - and formulating this as a general rule which she uses quite often at different teaching situations lateron and by this proves to be rather stable.



The important experience that they needed two different connections to make the bulb light together with her high value of positive and negative charges for her are best expressed with this general rule:

> 2. Suppose you wanted to tell a friend, over the telephone, a general <u>rule</u> that would enable him or her to make a bulb light. From what you have observed and discussed in this activity, write down the most general rule that you can.
>
> *L (written answer): You need to have both negative and positive charges to conduct electricity.*

After writing this rule Lynn in her additional verbal explanations goes two steps further, she brings positive and negative charges and the production of light in connection with this idea, also generalizing it:

> *L: Well, when I thought general, I didn't think we were talking about this specific experiment, so I just said that if you're gonna produce some type of light, you need to have positive and negative charges to conduct any kind of electricity. For any electricity, I guess, you just have to have those two charges.*

And after a while she adds yet another feature to it bringing the process of neutralizing as an essential part of the whole circuit process into play:

> *L: The, the base needs to touch, as well as another point to neutralize the charges coming in.*

Because of its later importance for all three students’ cognitive development in session 1 and 2 we call this idea an intermediate conception: "A proper electric circuit needs the positive and the negative."

<u>Analysis of intermediate conception and of learning process of Lynn with respect to the role of "prior conceptions" and "teaching input"</u>

The middle column of the following table contains the essential features of the new intermediate conception. In the left column we briefly write down what facets of prior conceptions might be contributing to the development of the intermediate conception. In the right column we speculate about the essential impacts from teaching ("teaching input (TI)") which contribute to this development. The new intermediate conception "A proper electric circuit needs the positive and the negative" seems to be created out of the following facets:

Facets of prior conceptions (PC) (contributing to development)	Facets of intermediate conception (IC) "it needs the negative and the positive" (newly developed)	Elements of teaching input (TI) (contributing to development)
- you need two wires to jump a car - high interest in positive and negative charges and their dynamics (hypothesis) - electrons and protons - high tendency to think with particles and their movement - perhaps special experiences (e.g. with jumping a car)	- you need two different connections - current always needs positive and negative charges - light in the bulb is produced by positive and neg. charges - a circuit needs protons and electrons to work properly	- experience from own experimental success (!) - teaching about forces between charges two weeks ago - teaching about protons and electrons

<u>Use of this intermediate conception throughout the learning process</u>

Some time later <u>in session 1</u> conceptions about current (carrying energy) were explicitly discussed. Lynn having her "intermediate conception" in mind poses the following question being not in the direction of the teachers line of thought:

> *L: What does this current consist of that takes the energy?*

And immediately G follows her thought:

> *G: The positive and negative charges.   H: Yes.*
> *L: It's the atoms of the positive and negative charges that take it along with it?*

The idea is now developed further by using facets of a microscopic view with electrons and protons with it. But especially Lynn is testing the new ideas against the full range of meanings of her conception about positive and negative charges. Lynn is trying to stay with her theory of positive and negative currents. She tries to be consistent:

> *H: The protons just stay. Have you any idea why the electrons should move this way? {Pause of about 5 seconds.)*
> *L: I just don't understand...If the protons are staying there. They're not traveling to the bulb. You're not getting the combination of the two charges up there.   ...*
> *L: I'm saying, I'm saying if we're only getting negative...If we're only getting electrons, which are negative, right? If we're only getting that negative going to the bulb,...*
> *L: There, there's protons inside the bulb that are combining with to give the...to give off the light?*

Her idea of light being produced from positive and negative charges is in contradiction to the teacher's idea that only electrons are moving to the bulb.
The teacher goes on:

> *H: ... But the idea is the electrons are moving through this wire. And by moving they hit those atoms which are in this wire. And the atoms get warm.*
> *G: Which atoms?*
> *L: Neutralized atoms.*
> *L: So, does the bulb have both negative and... Electrons and protons in it?*

Lynn sees "neutralized atoms" as a result of positive and negative coming together inside the bulb.
At this point G changes the idea, she seems to grasp the teacher's idea easier because she is not so strongly devoted to Lynn's intermediate conception:

> *G: It isn't... It does... The protons don't even matter. It doesn't...It's not the fact that they're going....That they're positive and negative electrons in there. That...I mean, um, atoms in there...That's not what's happening. What's happening is the neg...The electron...The negative...Wait...The electrons are going in there and it's moving the atoms. So, the protons have...Doesn't even matter if there's protons in there or not. So, that doesn't, that even come in play.*

L: And protons don't move. The only thing to move would be electrons. That's the only reason that it goes? Okay

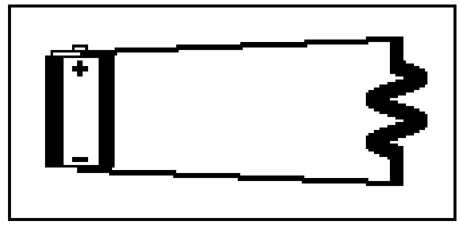
For Lynn the intermediate conception is so powerful that she has difficulties to get the teacher's idea of moving electrons as the main effect.

In session 2 the students got additional equipment (more wires, ...) and again were trying to light the bulb. Then they again were asked for "a general rule to make the bulb light". Lynn's written answer was:

L: Have both negative and positive charges. Negative coming through wires from a closed circuit (battery) to the bulb and back to the battery.

In her second sentence she combines already with the second intermediate conception "microscopic view of current". Later in the same session Lynn is drawing a circuit diagram with the computer. She does it quickly as follows:

L: (Clicks onto the wire symbol and returns cursor to battery top. Moves cursor to top of bulb symbol. Moves cursor from the bottom of the battery symbol to the bottom of the bulb symbol.)



Her two movements on the screen from battery plus to bulb and from battery minus to bulb correlate perfectly to her intermediate conception.

In session 3 when discussing a pressure diagram with two batteries in series and one bulb Lynn clearly uses the prior conception of current, here with the term "pressure" and with a notion of consumption, which in this case yields a correct conception of pressure drop:

L: We think that if there's this much pressure going in, it's gonna make this light really bright and it's gonna use so much that's it's gonna come out really low.

Additional comments

These first tasks #2, #3, and #4 in session 1 and the feedback they give from successful experiments worked as a very effective teaching input as can be seen from the following statement from Lynn (and similar statements from the other two students). This is perhaps due to the fact, that a conceptual understanding on the level of a “General rule to make a bulb light” is a different cognitive domain than the concept “current” and much easier to be developed, as was found more than twenty years ago (Niedderer 1972).

After all of these explanations and success with finding the right connections between battery and bulb Lynn expresses some good feelings having learned how to do it, without current theory, but with some general rule:

L: I've said that it seemed like the whole idea of electricity seemed complicated until you break it down into these little things. It's like, well, you know, positive, and then negative. And there's, an, an, how, where they need to be touched. I mean, once you break it down, if you just think of electricity, you think, Oh! It just sounds so complicated. But when you have little pieces like this, and you can piece them together; all the little pieces make sense.

This is clearly to be seen as a first **"big success"** with electricity, showing a positive resonance between teaching and learning, between prior cognitive structure and teaching activities.

4.1.3 New intermediate conception "microscopic view of current”

General description

Lynn is coming to a new intermediate conception "microscopic view of current" in which she is describing current as movement of electrons driven by repelling and attracting forces from minus to plus. But no strict conservation law is valid, electrons can be taken away in a bulb.

Teaching activity

During discussion of a circuit on the white board the teacher poses questions about “current” and gives some pieces of information to introduce a microscopic view of "current" in order to prepare the later introduction of "pressure". At first he tries to address explicitly students’ concept “EDL-current”:

> *H: It is important to see that current can be understood in different ways. You were talking about energy; at the beginning. And that energy is going from the cell to the bulb. And I would say to you this is obvious. You should be sure this is happening. Energy is going from here to here.*

Then he starts to contrast this with a more scientific idea of “SCI-current”:

> *H: But, you could also think of current in a different way. That it's stuff. It's a material. Which is carrying the energy. Which is not the energy, itself. What do you think would be the difference between those two pictures?*

Qualitative analysis of transcript: Lynn's Cognitive development

During this introduction of the concept of a microscopic view of current by the teacher Lynn is doing her own cognitive development. She, in her first contributions in this dialogue, shows clearly that she is still working with her former intermediate conception "it needs the negative and the positive" to understand the new concept:

> *H: Yes, it is carrying the energy. What then is the current and what is he doing. And how is he working?*
> *L: What does this current consist of that takes the energy?*
> *G: The positive and negative charges. H: Yes.*
> *L: It's the atoms of the positive and negative charges that take it along with it?*

In the last statement Lynn is adding a “microscopic view” to “charges”. This is continued when the teacher adds another piece of information:

> *H: Yes, well physicists have a model which says there are positive and negative charges. And the positive charges are not moveable. They stay where they stay. ... And the negative charges are moving. C: ...*
> *H: Yes. ... And the negative charges are moving. Well, ... , what would you think the negative charges are moving? What direction?*
> *C: … G: … C: …*
> *L: I think they'd be leaving the bulb. I mean, leaving the battery, I'm sorry! Leaving the battery.*

Now Lynn again and again constructs this actively in her own mind, coming to a conflict between her idea of positive and negative charges producing the light in the bulb together (see above in 4.1.2).

> *L: I just don't understand...If the protons are staying there. They're not traveling to the bulb. You're not getting the combination of the two charges up there. ...*
> *L: I'm saying, I'm saying if we're only getting negative...If we're only getting electrons, which are negative, right? If we're only getting that negative going to the bulb,... ...*
> *L: There, there's protons inside the bulb that are combining with to give the...to give off the light?*

The teacher again adds some information:

> *H: But the idea is the electrons are moving through this wire. And by moving they hit those atoms which are in this wire. They get movement from the moving electrons, so that they get heated.*
> *G: Which atoms?*

L: Neutralized atoms. ...

L: So, does the bulb have both negative and... Electrons and protons in it? ...

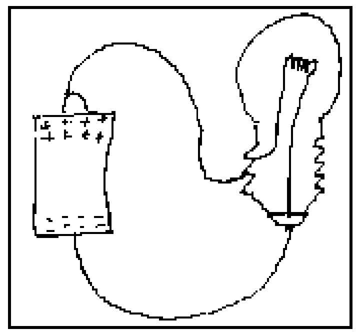
L: And protons don't move. The only thing to move would be electrons? That's the only reason that it goes? Okay

Again, inspite of new pieces of information, Lynn works along the conflict stated above between her idea of positive and negative charges producing the light together. Finally she has finished her own reasoning and seems convinced. The other students meanwhile discussed questions of the movement of the electrons. The next teaching input yields no contribution from Lynn at all.

H: 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. We can understand something that was hard to discover for you now from this model. You need two wires because the electrons come in and out. And if they don't come out, no movement. What would happen in your imagination if we had only one wire?

The teacher now with the aim of introducing "pressure" is giving more explanation on the "microscopic view":

H: Physicists say: Well, it's so crowded here, they push each other. You have seen those experiments with the spoon. You have seen a repelling force from equal charges. So they push each other in this direction (where there are not so many electrons)



Now Lynn contributes with ideas about a microscopic view of motion and forces of electrons:

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..

The expression "repels those away from" in fact can be seen as a first form of a causal relation between force and motion in the microscopic view.

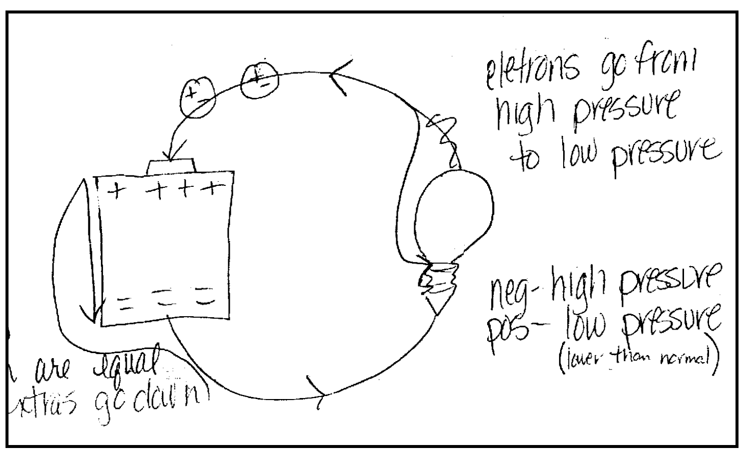
And after a while:

L: So it goes...The protons are like, repelling. C: ... G: ...

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.

Here Lynn seems to have a serious misunderstanding thinking that electrons are repelled from protons. This is also maintained in her final written conclusions with picture:

L (written):
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.



This picture and the written explanation clearly show a microscopic view of current. The additional writings about high and low pressure were added later in the session. We see them as rather formal characterization based on the former intermediate conception that you need the negative and positive.

Analysis of learning process of Lynn with respect to the role of "prior conceptions" and "teaching input"

The middle column of the following table contains the essential features of the new intermediate conception. In the left column we briefly write down what facets of prior conceptions might be contributing to the development of the intermediate conception. In the right column we speculate about the essential impacts from teaching ("teaching") which contribute to this development:
Lynn's new intermediate conception "microscopic view of current" seems to be created out of the following facets:

Facets of prior conceptions (PC, IC) (contributing to development)	Facets of intermediate conception (IC) "Microscopic view of current" (newly developed)	Elements of teaching input (TI) (contributing to development)
- PC "force and motion" - IC "A proper electric circuit needs the positive and the negative" - PC "EDL-current"	- The electrons are repelled (from protons !) - they exit and are pushed to bulb - make movement in bulb - are attracted back by the protons - creating a circular movement (number of electrons NOT conserved)	- only electrons are moving - it's so crowded here, they push each other - positive and negative charges - two views about "current": fuel or water

Analysis of intermediate conception by comparison to "prior conception" and "scientific concept"

We try to show the changes in Lynn's concept of current by comparing it both to the prior conception and the scientific concept:

Facets of prior conception "EDL-Current"	Facets of intermediate conception "microscopic view of current"	Facets of scientific conception "SCI-Current"
- substance "electricity" - containing energy (like fuel)	- electrons, charge - more like fuel (?)	- process - transporting energy (like water)
- going one way: battery - wire - bulb - "something" is consumed - battery is active, bulb passive	- forming a circular motion **without** mass and flux **conservation**, driven by the pressure (not difference) from the battery	- forming a circular motion with mass and flux conservation, driven by the pressure difference from the battery
- flow 'to' (movement necessary) - amount of current means: volume or strength of "electricity" (current)	- flow 'through' (movement necessary) - amount of current: more related to number of (consumed) electrons than to speed	- flow 'through' (movement essential) - amount of current means: number and speed of moving electrons

The main **gain of the intermediate concept "microscopic view of current"** seen from the prior concept is:
- current is related to movement (flow) of electrons and charges
- there is a circular motion, driven by something (pressure)
- the amount of current is related to the number of electrons

The main **shortages of the intermediate concept current** seen from the scientific view are:
- current is still seen as substance containing energy, like fuel, not as a process, like water
- the circular motion is **not** seen from a conservation of flux point of view: At the end of long reasoning about pressure in a circuit with two bulbs in series she again violates electron conservation ("Give me some of those electrons back").
- the circular motion is driven by pressure, not pressure difference
- the amount of current is more related to the number of electrons than to their speed. What does "high current" mean? Lynn has the right intuition that it relates to "how fast it is going", thus talking about the speed of electrons ("not as much movement"). But yet this important aspect of a scientific concept current is not very active in her cognition. No really clear distinction is achieved between the two concepts "current". The essential missing point is: In "EDL-current" the movement of electricity is only necessary to bring it to the bulb. In "SCI-current" movement is the essential criterion creating the effects like heating and being causally linked with voltage or pressure difference. The amount of current is related to the number of electrons **and** their speed.

<u>Further development of the intermediate conception "microscopic view of current" in session 2</u>

After additional experiments in session 2 with one battery and one bulb students were asked to formulate a general rule:

> *L: Have both negative and positive charges. Negative coming through wires from a closed circuit (battery) to the bulb and back to the battery.*

Here Lynn combines both intermediate conceptions from session 1 showing these conceptions to be of some stability. She also adds the circular motion to movement of the negative charges (electrons ?) here. Later after some discussion of pressure and current in a simple circuit current is clearly related to a microscopic view, to the movement and flow of electrons, sometimes charge:

> *L: The current is the flow of electrons.*

The discussion is then continued, and the teacher asks directly about current and pressure in those circuits. Lynn at first is talking about "high-current" showing for the first time a facet connecting high current to the movement being "fast". This might be one of the most important facets of a better current conception. But it is not very often used by Lynn.

> *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.*

During this discussion Lynn also starts for the <u>first time with a very important idea, connecting high current and fast speed of electrons!</u>

Then a spontaneous idea leads to an experiment with two bulbs in series. During the discussion of current and pressure in this circuit Lynn is saying:

> *L: ... 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 ...*

The movement, flow, and speed of electrons still has **more** the meaning of bringing electrons to the bulb and back to the battery, and is not seen as the essential aspect of amount of current. Amount of current is still more related to a substance (number of electrons) than to their speed. Lynn is discussing a consumption idea - no conservation of electrons - combined with a microscopic view of electrons and their movement. And shortly after, still working on the same problem, Lynn shows again a microscopic view with consumption (no conservation) of electrons:

> *L: ... 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.*

Later on still in session 2 an open circuit (connection to plus side of battery is interrupted) is discussed in computer video representation of pressure diagram. Lynn is drawing and thinking about what pressure to assign to the open end:

L: ... But, since it's not having this pull back here. This attraction back to the...the protons, I don't know...I have...I (inaudible)

This idea of attraction to the positive was not given from the teacher but is part of her conception of a microscopic view of Lynn and clearly related to her first intermediate conception of positive and negative charges. She uses this idea several times throughout the whole process.

4.1.4 Lynn's new intermediate conception "pressure"

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

General description

Lynn is coming to a new intermediate conception "pressure": Electrons go from high pressure to low pressure. High pressure is at the negative end of battery, normal in (or after) the bulb, low at the positive end of the battery. Pressure can be released or built up.

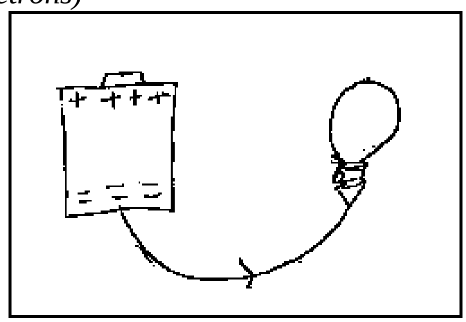
Teaching activity

The teacher introduces "pressure" while discussing a simple circuit at the white board:

H: ... Physicists say: Well, it's so crowded here, they push each other. You have seen those experiments with the spoon. You have seen a repelling force from equal charges. So they push each other in this direction (where there are not so many electrons)

The teacher goes on with pressure with a new question, related to a circuit with only one connection between battery and bulb:

H: ... Now let's think of an additional one. Pressure. ... ... Let's start again, with no wire here. ... What would you think, in terms of pressure, is happening? The electrons will start and go over there (points from battery to bulb). And then, soon, very soon, this movement will stop. Why did it stop? Or why goes it at first and why will it stop? Perhaps make use of the term pressure. ...
H: ... But the question is why does it move in the first moment and why does it not go on moving?



Qualitative analysis of transcript: Lynn's Cognitive development

Lynn now is using good ideas with "pressure":

L: The pressure would build up inside. The bulb wasn't allowing any to expel out. There would be too much in there, and it would like, - ...
L: It's starting to get too much. H: Yes. And what is with pressure? ... C: ...
L: There's no release of pressure, though. There's gotta be some release to keep the, the movement flowing so that these continuing electrons keep going through the bulb.

So in her conception of pressure some reasoning with facets like "build up of pressure" and with "release of pressure" is possible. It's also interesting to see that Lynn in this early stage has a causal connection between pressure and movement, that means between a microscopic view of current and a conception of pressure! This was the hope of using this conception in this teaching approach. But often in later reasoning the conception of "pressure" by Lynn is reduced to the facet "high pressure at positive, normal pressure at bulb, low pressure at negative", used like a general rule. The special meaning of "normal" pressure for Lynn was already explained in 4.1.3. with her discussion of protons and electrons inside the bulb and seeing "neutral atoms" as the result of them producing light. In her final writing of this session 1 Lynn already uses the formal rule "negative is high pressure, positive is low":

L (written): electrons go from high pressure to low pressure
neg - high pressure pos - low pressure (lower than normal)

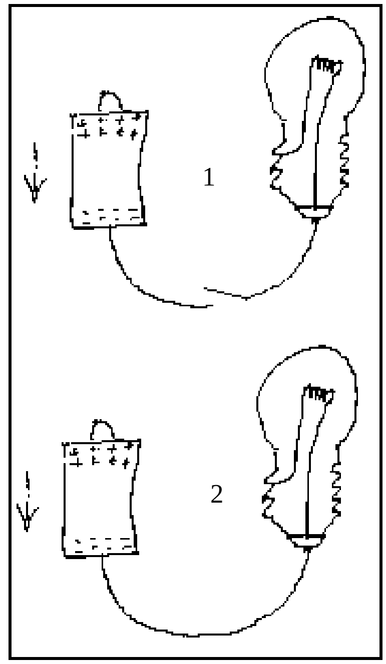
After writing, the two circuits 1 and 2 are discussed. The teacher again modifies the question:

H: So, now we connect it (2). What's happening with the pressure?

Lynn is using the pressure idea (after hint from the teacher) to cope successfully with this challenge:

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

Already in this early stage of development Lynn uses own reasoning with pressure with facets like "release of pressure" and "build up of pressure".



Further development of this intermediate conception "pressure" in session 2

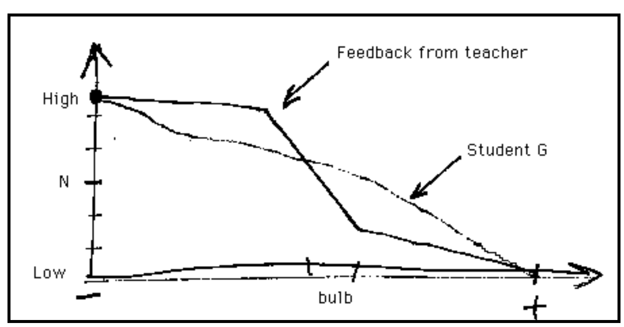
This further development is described by observing the facets of Lynn's intermediate conception "pressure". We will see some of the facets already shown in session 1, and this means they have some stability, but we also will observe some new facets.
Her general rule at the beginning of session 2 reflects no reasoning with pressure! (see 4.1.3) Instead of it uses the old idea of the first intermediate conception with "both negative and positive charges" together with a microscopic view of a flow of charges in a closed circuit.
Afterwards, the new circuits with one bulb and one battery are discussed with the explicit question "What do you think about current and electron pressure in those circuits?". Lynn remembers "high" and "normal" but she comes to "no pressure" instead of low:

L: Didn't we say that there was like, high pressure inside the battery and then it got to be low pressure when it got up to be the bulb? Then it became no pressure?

Shortly after Lynn uses another important facet of a good conception of pressure. This seems to be a first facet in Lynn's mind which could be developed to a causal relation in the direction of Ohm's law:

L: Since they go from high pressure to low pressure.

Then the teacher is suggesting to draw a diagram with pressure on the y-axis and the distance along the circuit along the x-axis. While G is drawing, Lynn is giving the following statement:



L: I think that it's a really high pressure when it's coming out...from the negative end. Because they're all being pushed down there, you know, so there's high pressure flowing out. And then once it gets in there, you...It gets to be a lower pressure. They're not being forced. They're...they're kind-a flowing through there. And they're moving along as they go through. And when...As they're exiting, there's kind of a...high pressure that's pulling them back down into the...well, maybe not a high pressure, because it's pulling...It's not really pressure. It's...just kind-of a trick ...

This statement contains the following facets of Lynn's intermediate conception "pressure":

- high pressure at negative
- high pressure because of being "pushed down there"
- some connection to flowing and moving. Interesting enough: it is the pressure here which is flowing and this for us is a hint that the old prior conception of current with the main meaning of fuel and using different names for it (power, electricity, and now pressure) is to be seen in this statement.
- the drop of pressure along the bulb (which is supposed to be also connected to the old prior conception of EDL-current and current consumption)
- the special meaning of attraction from positive to the pressure is to be seen again here.

After feedback from the teacher Lynn is talking about pressure drop again.

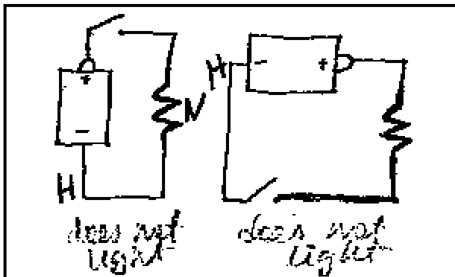
L: So it makes a pretty drastic drop right at the bulb.

Here a new facet about pressure drop is used which later in the learning process is clearly to be seen to be connected to the old idea in the prior conception of current consumption. In her next statement she stresses the "drop of pressure" which is quite helpful to learn more about "pressure loss" but - as is to be seen from many other statements [6] - for Lynn also has the meaning of current consumption:

L: The current is the flow of electrons. There is high pressure until the bulb, then there is a big drop while going through the bulb and then a gradual drop returning to the battery.

In this statement both intermediate conceptions "microscopic view of current" and "pressure" come together, probably with a bias of the prior conception of "everyday life current".
Then she is using "pressure" to make predictions for given circuits in "the last two models":

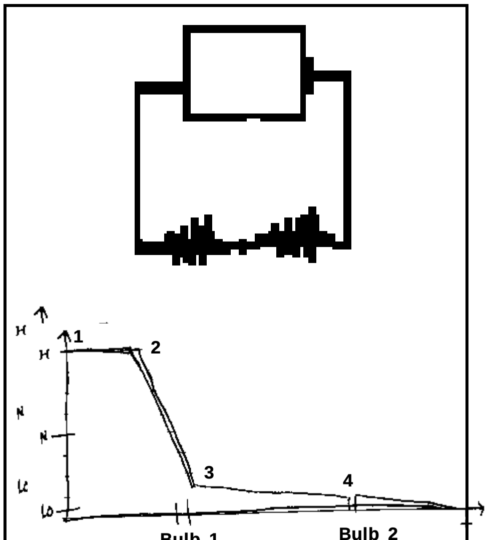
L: The first two models would lite. The last two wouldn't. The break into the wire would release all pressure and there would be no pressure returned to the battery.


"the last two models"

Here again Lynn is using intuitive reasoning with release of pressure (in a wrong way but coming to the right prediction) which clearly is one facet of her pressure conception.

Then a spontaneous idea to put a second bulb behind the first one leads to a lot of discussions about current and pressure in this circuit. Lynn starts her reasoning about this situation by using current, pressure, electrons, and power synonymous to "current consumption" in the sense of the prior conception of "EDL-current" (see 4.1.1):

L: I think...that...if...(inaudible) is, you know, we discov...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...



Lynn's drawing

During this discussion Lynn also repeats the idea of some connection between pressure and the direction of movement of electrons:

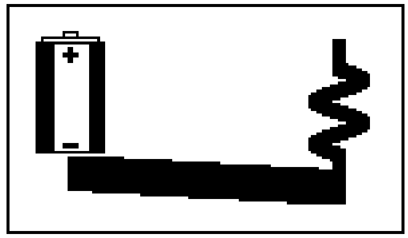
L: I think what happens is that.. This would be fine, but as soon as it gets to here, it's getting drained, cause it doesn't have enough...to light this. So it's actually pulling ...It's pulling electrons...pulling...Yeah. It's pulling electrons from here. So there's not as much movement inside here which makes it a less light...because this one needs it. It's not so

[6] see below and 4.1.1

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?

Besides this cluster concept based on the prior conception of everyday life current Lynn here is also using the facet of movement based on pressure (or electrons or power). While drawing Lynn continues:

L: "I was tryin' to light this over here (1 to 2), but I didn't get it right. It should be, what? A little bit farther out here (2), and then start coming down twist it into the bulb (2 to 3). So, let's see. There's gonna be...a decreasing pressure here. An all of a sudden it's gonna get to that bulb (4). And it's gonna take - even more , so it's gonna..just keep...decreasing, I guess. ... And then we'll...what...I...I know what I think, it's...hard to draw. But does that make sense, though? That, like...it's got this current. It's going just fine (1 to 2). Okay, this high pressure's coming out here. And it's going in here and it lights this (first bulb) up just fine.

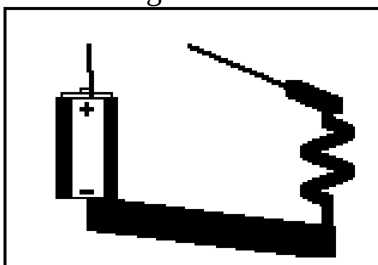


The next teaching situation with pressure is when students start to draw pressure diagrams with the computer. Without hesitating at all Lynn is taking "high pressure" (thick line) starting from the negative. It again tells us something about pressure in relation to negative and a microscopic level: This conception ("negative is high") for sure is active in all three students' thinking.

L: (Clicks onto the "High pressure" symbol & moves the cursor to the bottom of the battery symbol to the bottom of the bulb symbol.)
L: (Clicks onto the "Normal pressure" symbol & moves the cursor towards the screen.)
L: I wanna say that there's...There's normal pressure going through here (the bulb), right? ...
L: It's a gradual decrease. I guess it was normal coming out.

The next statements are related to a first open circuit shown in the diagrams to the right:

L: Oh! Well, there would be no...There would be nothing (pointing with arrow on the screen to positive end of battery). There would be nothing there. This is what (inaudible). ...
L: And then if, if it got cutoff right here (pointing with screen arrow to upper wire behind the bulb). All the pressure would be re...leased. It would be no build up of pressure. Cause it isn't supposed to be

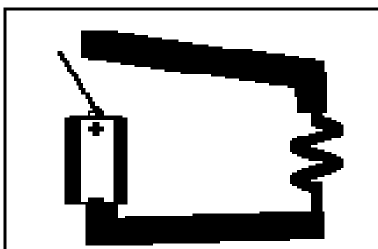


Lynn's drawing

These statements show again a strong tendency to use the pressure conception together with own reasoning using the facets "build up" and "release" and "spit out" and even with forces of "pulling" from the positive. They show that Lynn's pressure conception is <u>not</u> only consisting of the rule "negative is high, bulb is normal, positive is low".!

The next statement in addition again shows her first intermediate conception ("it needs the positive and the negative") with her expression "kinda neutralize":

L: I don't think the...It seems like...I mean, I know it's leaving here- That's all right. And it's leaving here (the battery), like a high pressure. And it's going in here (to the bulb) and it's supposed to...um...kinda neutralize, or whatever. Get...Get more of a normal pressure. Not so high. But, since it's not having this pull back here. This attraction back to the...the protons, I don't know...I have...I (inaudible)

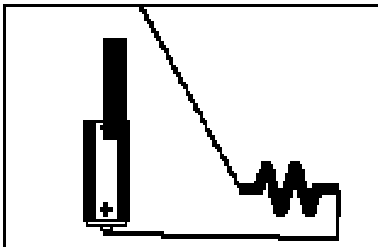


Feedback from Teacher

At the end she does <u>not</u> understand the high pressure behind the bulb, perhaps because of missing information about wires and release of pressure!

The next statements relate to a second open circuit (diagram):

H: And what, then happened the first moment when you make a contact to (+) here? G: ... H: ...
L: It'll click with just a tiny bit of light. H: ...
L: Cause there's enough pressure when it's -
L: I just didn't know there could be any pressure in here at all if there's no...H: ...
L: ...pressure from the bulb. If there's no connection at all, where is it gonna get its pressure?



Feedback from teacher

A final discussion in this session is started after an experiment in which the bulb is lighted much brighter by a battery having 6 V. Lynn's statements here show that she is making a connection between Volts, charge and pressure, but she is not talking about current. So, these statements could be seen as a hint that she is differentiating somehow current and pressure.

L: It has more volts. H: ...
L: Volts...or something? More charge. H: And what does that mean?
L: More charges. More pressure. C: ... H: ... C: ...
H: It's brighter. Why is it brighter?
L: There's more... more volts that are giving it -

This unfinished sentence perhaps is again a hint that there is some kind of causal thinking towards Ohm's law.

<u>Analysis of Lynn's conception of “pressure” in session 1 and 2</u>

In the following table Lynn's intermediate conception "pressure" is described by a list of main facets. These facets are compared in the right column to facets of the scientific concept of pressure.

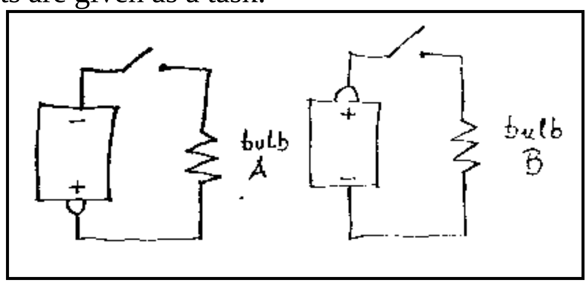
Facets of Lynn's intermediate conception "pressure"	Facets of a scientific concept "pressure"
- rule: "high" pressure at negative, "normal" in the bulb, "low" at positive - pressure is a result of many (extra) electrons - high pressure is from repelling forces (even from protons), low from attracting forces	- pressure of a gas is depending on <u>particle density</u> and <u>temperature</u> (movement)
- pressure can be "built up" or "released"	- pressure can be "built up" or "released"
- electrons go from high pressure to low p. - attraction from positive has some strange impacts on pressure	- the fluid or gas (current) is moved by pressure differences (Hagen-Poiseuille), the higher the pressure difference the higher the speed
- pressure can be lost along the circuit - pressure can diminish along one wire	- fluid motion is maintained by a pressure gradient along the pipe
- "pressure" itself perhaps has the meaning of pressure difference	- voltage relates to pressure <u>difference</u>
- a break into the wire would release all pressure	- pressure (normally) is released at an open end
- an unconnected wire is an open end	- an unconnected wire is a <u>closed</u> end

Lynn uses the assertion "high pressure at negative, normal in the bulb and low at positive" like a general rule. This rule is used without further reasoning and often over generalized, as a memorized fact (H-N-L or H-H-L-L). Further verbal explanations of the teacher got no resonance in Lynn's reasoning (Examples: labeling of pressure diagrams in open circuits.) This is especially true in further situations with more complex circuits. Pressure along the circuit is also used with another idea: a microscopic view with loss of pressure and electrons (**without** conservation of the number of electrons): "but since this is taking...pressure and electrons away", obviously coming "from something is used up" in the prior concept "EDL-current".

But there is also some effort to intuitive reasoning with pressure: release of pressure (e.g. Lynn is using the label "NONE" at three places), repelling out and being pushed down means high pressure, more charge (more electrons) means more pressure.
Proto-causal relations like "electrons go from high pressure to low pressure" are used sometimes, not very active yet. Pressure is a cause for the movement of electrons (not “pressure difference”); probably “pressure” from students already has the meaning of “directed pressure” which would be similar to “pressure difference”. This facet is a nucleus of Ohm's causal relation.
Lynn gives very much attention to the attractive force from the positive end of the battery, but she has difficulties to describe this in terms of pressure or pressure difference
Many of these facets have been subject to explicit teaching, but these formulations of meaning are taken from Lynn's statements. We see them as Lynn's cognitive responses to the teaching input. These facets of Lynn's conception of "pressure" which are started already in section 1 seem to be a very good starting point to develop a reasonable and powerful concept pressure. Later on in the learning process "pressure" very often is used rather formal more or less with the rule: "high pressure at negative, normal pressure in the bulb, and low pressure at positive."

4.2 Development of Lynn's "microscopic view of current" in sessions 3 to 5

At the beginning of session 3 the following two circuits are given as a task:



L: Bulb A won't light, bulb B may light slightly for only a moment.
The movement from the electrons may be enough to make the light come on, but without the pull to the protons, it will not stay on. The electrons in A never get to the bulb so it won't come on at all.

This statement again clearly demonstrates her microscopic view with the special feature of attraction from positive.
Another good example of using a microscopic view where the teacher not even did expect it occurred still in session 3 while drawing pressure diagrams with two batteries:

H: What is it (the battery) doing between its ends? Between plus and minus?

The teacher expects something with pressure difference!

C: They're opposite. H: Yes. They are opposite. Yes.
C: What are they doing? H: Yes. What is the battery -
L: Moving electrons.

The battery is moving electrons!

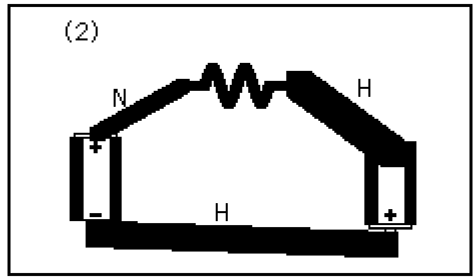
During a discussion of two different bulbs in series in session 4 Lynn again uses a microscopic view:

H: ... What do you think about current 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)

Lynn is asking the right question here, but she also clearly expresses uncertainties at this crucial point for a scientific understanding of current. Very often this term “high current” later on seems to have this “double meaning”.

4.3 Development of Lynn's conception of "pressure" in sessions 3 to 5

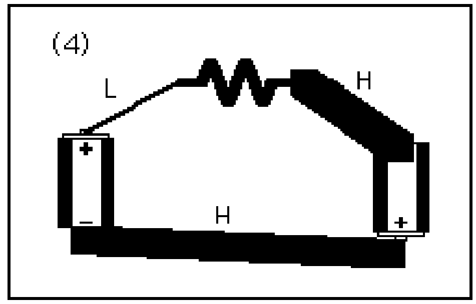
In session 3 students are trying to light a bulb as bright as possible with two batteries. After having found a solution they try to model this circuit with a computer pressure diagram. They work long time and hard on this task producing three different solutions, the last being near to a final feedback solution from the teacher. After students have done their second pressure diagram Lynn starts reasoning:



L: I'm sorry. I...I...I don't think there should be high pressure going into the positive end of the bulb...of the battery on the right hand side.

L: Well, maybe high leaving it...the bulb on less from the negative end, but...going into the positive end on the battery on the right...I don't think it should be high.

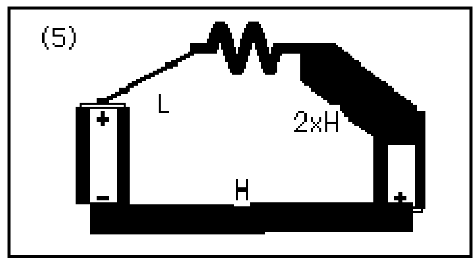
Here again the stability of this facet "low at positive" (and "high at negative") of the intermediate conception "pressure" is seen in Lynn's reasoning.



After the next pressure diagram (4) Lynn again is using the same idea:

L: Hasta be high comin' out of there. ... Wait a minute, though. Going into the positive, I still don't think that should be high pressure.

L: I just feel like every time we've talked about going into a positive end, it's been lower and I guess that's because of the bulb.



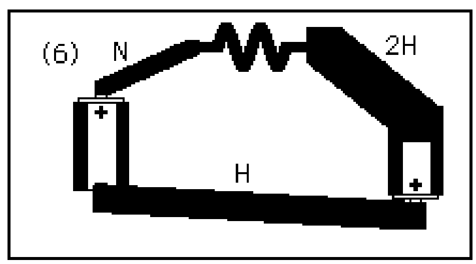
With the next pressure diagram (5) Lynn starts an important construction process towards pressure difference:

L: You just have to remember that...that when it's coming...like...a negative, it's...it's higher than normal, and...a positive is lower. So there's this variation in between those two.

With the term "variation between those two" she starts seeing the relative differences. She then does relative thinking with two batteries while drawing a new diagram:

L: Well. This thing is called "Two times high." (2X high) H: Two times high. Yes.

L: So it's getting one pressure from one battery and the second from the second battery. So that means it's two times...regular pressure.



Then while comparing diagram (5) and (6) she says:

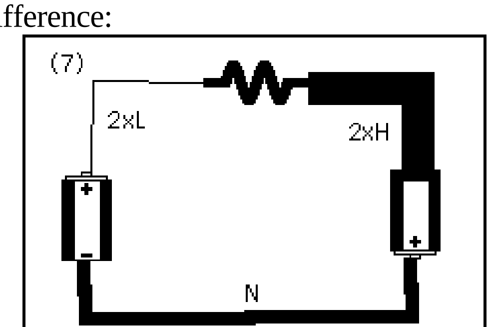
L: There it lost less pressure inside the bulb in this bottom case. H: Uh-huh.

L: So that it's not coming out low pressure, but it's just coming out normal because it's so high pressure that's coming in there.

So she is thinking in differences now but still not totally consistent.

After feedback from teacher (7) she immediately gets the main difference:

L: Oh! It's real low comin' outta there!



Feedback from teacher

Coming back to her old idea again:

L: I just don't understand why there's only normal pressure coming out of this...this first...this battery here.

C: Cause it's extra low there.

L: Where's it starting though? Isn't it st...

This is a good question showing her efforts to really understand the relative view. And then she gets the fruitful idea:

C: I can understand how it's extra low to, to normal, because it's...it's...

L: (Finishing C's sentence) It's taking two steps.

C: Right.

L: Just like it took two steps from here to here.

Now she is thinking in "steps" of pressure difference. But she goes back and forth again:

L: But I just don't understand why , if say we didn't know this happened here. Like, why wouldn't this pressure be coming outta there...because we know that electron pressure is higher than normal. C: But this is higher than that norm...than that.

L: This isn't normal.

L: We think that if there's this much pressure going in, it's gonna make this light really bright and it's gonna use so much that's it's gonna come out really low.

At the end she uses the old idea of "use of pressure" (pressure consumption) related to the prior conception of everyday life current again!

The teacher then tries to foster this process:

H: Yes. Yes. Now, let's look to the left battery. What, what does the left battery do?

L: It's getting this really itty bitty low pressure and it's only spitting out normal pressure, but I thought, - H: - So what is it doing?

L: - I thought as a general rule we made, though, was that, (pause of about 3 seconds). Am I screaming? C: No.

L: I thought this general rule was that electrons always had a higher than normal, and that the protons were lower than normal. And this normal was inside the bulb.

But Lynn again is going back to her old rule with pressure, one facet of her intermediate conception of pressure! This gives evidence to her high obligation to her own consistency which is not the same with the other two students! [7]

But she is going on:

G: That is extra high. C: Right. And then, in here is like, low. (inaudible)

L: And then extra low would be coming out. That would be equivalent to high, normal, low.

Perhaps we can think of battery as a "pressure booster". A 1.5V battery always boosts the pressure by two "steps" on the pressure scale. And shortly after she gets the idea even more generally:

H: ... Now, we have a different situation.

L: Well, it's comparatively speaking, to the high or low. I mean, - H: Yeah. Yeah.

L: It's just like, I'm tall. Well, maybe compared to Colleen, but I'm not tall compared to Kareem Abdul-Jabar. No!

A wonderful result, but this of course does not mean that the old ideas have all a sudden vanished: The conceptual ecology just has one more element.

Later in the same discussion about the same discussion about the feedback from teacher in pressure diagram (7) Lynn expresses twice the above mentioned idea of battery as a "pressure booster":

H: What is the main thing a battery does? What is, what -

G: ... H: ... but now give an answer in terms of pressure. What does it, in terms of pressure?

G: It takes the pressure that it gets and it adds to it? H: Yeah.

L: The chemicals add pressure to the electrons and - H: ...So it makes a pressure...

L: Higher than what came in.

And shortly after:

L: I think that the rule stands. It still, I mean we still have the same rule, that there, this is always gonna be higher pressure. But it's only comparatively speaking, to the pressure that's entering in at first. C: Um-hum.

L: So, that started out, really, really high. When it comes out, it's just gonna be really, really, really high. It just depends on the .... C: Right.

L: At what's coming in, right? H: Yes. ... G: I just got it.

In session 4 an electric circuit of two different bulbs in series is discussed. The following segments of Lynn's contributions to a dialogue during discussion of this circuit shows that she still struggles with the difference between pressure and current:

L: What do you mean by pressure?

L: Current pressure.

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[7] This special aspect of learning has to be analyzed seperately in full depth!

And shortly after:

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.*

L: The more volts we have, the higher the current. The higher the current, the brighter the light. The less passive components, the less resistance will we have. If we change any resistor in the chain it effects...

In her last comment for me it is not clear what Lynn means by "high current". From a physics point of view it could be related to the amount of charge or the number of electrons, and this amount could be consumed. On the other hand Lynn has in some rare occasions shown earlier that she sees some connection between the amount of current and the speed of electrons. So the meaning of "high current" could be related to both.

In the next short dialogue about 2 different bulbs in series she is talking about "direct current" to the first bulb near the negative side of the battery. This again shows that in her conceptual ecology the prior conception plays a big role:

L (written): A bright B dim

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.

L: Well, I said that the bulb A was brighter because it's getting a direct current here (pointing to the wire connecting it to the negative end of the battery). From the negative end of this battery. This one's dimmer because the pressure leaving here (pointing to the connection between the two bulbs) is a low pressure.

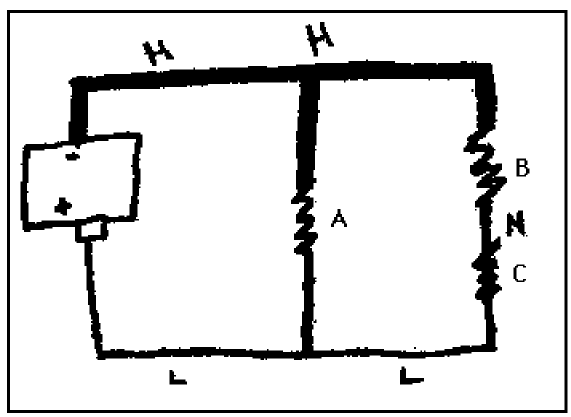
In session 5 a circuit with three equal bulbs, two being parallel and one in series is discussed. After a first very naive discussion with "following the path of the current" Lynn starts reasoning with pressure. She soon comes to a correct prediction of the outcome but with a wrong reasoning viewed from a physics point of view.

L: Well, here's the diagram (pointing to the diagram shown at the computer screen). So here's this pressure coming through and it'll split...one time. Isn't that what this looks like? I mean, the same thing?

L (written): B and C will be dimmer than A. B and C are splitting the pressure from bulb 2, but then the pressure will be whole when it reaches A. (prediction)

She thinks of pressure being split instead of current. This seems to give evidence for Lynn still having difficulties to separate the meaning of pressure and current. The same is true in one task of her final exam. The following diagram shows a drawing and written answer of Lynn in a new type of circuit in the final test:

L (written answer):
Pressure difference across bulb A: 0.75 V
Pressure difference across bulb B: 0.375 V



So again in her written answer she uses the idea (facet) of pressure splitting as the current is splitting. So bulbs in series as well as bulbs in parallel are sharing (splitting) the pressure which is totally in accordance to the prior conception of "everyday life current", where only one concept is relevant: current=electricity=power=energy=pressure=fuel.

We go on with session 5. After students have made their predictions and seen the experimental results they are prompted by the teacher to separate between current, pressure, and resistance. Lynn reacts by expressing her difficulties with this task:

L: Well, I...it's hard for me to just pick one piece. If I say the whole thing... H: Yes. Okay.

L: I think the pressure from...battery 2...pressure difference from battery 2 is coming through here high and it's having to split its pressure between these two things, and...so their resistance gets greater. That's why there's not as much light. Is that correct in saying?

In a later part of the same discussion she herself comes to questions about pressure again expressing her confusion:

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.

Lynn is starting to develop her pressure-current-concept with two first steps towards including pressure difference and build up processes with pressure:
- she quite often uses expressions which can be seen as a step towards using **pressure differences** instead of absolute pressures, like "comparatively speaking", "it depends on what is coming in", "now low is our normal", "it's taking two steps", "where is it starting so", "so there's this variation in between those two".
- she starts thinking in **build up processes of pressure** (instead of pressure being fixed attributes to special points of the battery and bulb) inside the battery and inside the bulb: "it's been lower and I guess that's because of the bulb", "so it's getting one pressure from one battery and the second from the second battery, so that means it's two times...regular pressure", "the chemicals add pressure to the electrons".
- she has difficulties in more complex circuits (different bulbs in series, equal bulbs in mixed series and parallel circuits) to distinguish between pressure and current.

5. Some general observations about Lynn's learning process

Conceptual development

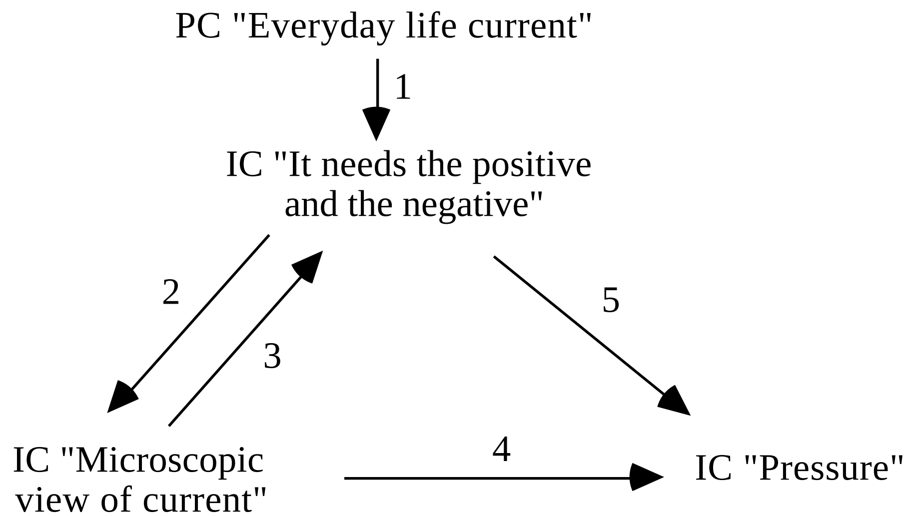
Lynn's conceptual development during this learning process starts with the well-known prior conception of everyday-life current. From there she develops a first intermediate conception "it needs the positive and the negative" which shows some stability and has quite important influences on the further cognitive development:

- It is used several times in session 1 and session 2.
- It is used in connection with a new intermediate conception "microscopic view of current" connecting negative to repelling forces and positive to attracting forces, using this metaphor in a strong way in many situations afterwards.

This first intermediate conception itself is not explicitly used after session 2, perhaps because of lack of adequate tasks. But its influence on the further conceptual development is powerful.

The next intermediate conception developed by Lynn according to the teaching input is the intermediate conception "microscopic view of current" related to a particle view of current with electrons and protons (compare the first intermediate conception above!), their movement and forces. Especially attracting forces are used by Lynn which was not intended by instruction.
The next intermediate conception is related to the concept pressure. In this conception one facet is very strong, the reason of this being explained already: negative is related to high pressure, positive to low pressure, and normal is related to the neutralizing process of positive and negative inside the bulb, so its meaning is more or less neutral. This is clearly related to the previous intermediate conception "it needs the positive and the negative".

All three intermediate conceptions contribute to this facet of Lynn's cognitive system, all four cognitive elements are related to each other:



1: There are negative and positive charges; you need two cables to jump a car
2: The microscopic view also very much emphasizes the role of the negative (repelling) and the positive end of the battery (attracting).
3: The idea "it needs the positive and the negative" is enriched by the microscopic view, they finally become one
4, 5: Both are adding to the pressure rule "high pressure at the negative, low pressure at the positive", giving it some special meaning used in Lynn's reasoning

In addition, Lynn uses intuitive reasoning with pressure about "build-up" and "release" of pressure right from the beginning in her own way. Perhaps this kind of intuitive reasoning is not represented good enough in the teaching materials. Later on in more complex situations Lynn therefore has typical difficulties with the pressure concept:

- Not differentiating between pressure and current
- Using pressure instead of pressure difference, perhaps having a meaning of the term "pressure" which is very close to "pressure difference"
- Changing the meaning of pressure from high at negative and low at positive to a pressure difference between those two of "two steps" which, for instance, can also be a double high at negative and normal at positive.
- Seeing pressure difference as caused by batteries, not clearly related to pressure differences across bulbs.

Conceptual ecology

If we try to paint a picture about Lynn's cognitive system in sessions 4 to 6 and in the final exams the best picture might be that of a conceptual ecology. In this special case this means that Lynn's thinking processes in the later part of the instructional process can be understood by using elements of the prior conception "everyday life current" in connection with intermediate conception "microscopic view of current" and intermediate conception "pressure", together with some further elements of scientific conceptions like a causal relation between pressure difference and amount of current, relating current to not only number of electrons but also speed of electrons. The conceptual ecology has to be seen like this: Always in new and complex situations Lynn starts with the prior conception "everyday life current" which means, for instance, that she uses ideas of consumption or splitting together with pressure. But giving her some time or small hints she starts to differentiate between current and pressure and pressure difference and uses good scientific thinking.

Conceptual development and instruction

We use the basic idea of resonance between teaching input and conceptual development (Glasersfeld 1992, p.33) to explain the success or failure of instruction. Examples of success in this meaning are the development of the intermediate conception 1 "it needs the positive and the negative" from own experiments and prior cognitive elements about positive and negative charges or experiences like jumping a car. There is strong evidence that students get great motivational impulses from their own success in rather simple experiments (e.g. find right connections between battery and bulb); writing a general rule after those experiences seems to be an adequate teaching activity, thus creating an effective teaching input.

A further "success" in this meaning is the development of a microscopic view based on prior ideas about force and motion of particles (like electrons) which are well known from research about students' conceptions in mechanics and the structure of matter. The teaching input in this case was comparatively small, only verbal explanation by the teacher together with a drawing at the white board. The microscopic view, e.g. adopting a particle view for current, then is used very often by Lynn in sessions 1 and 2 whereas it gets more rarely used in the later sessions. This is perhaps due to the fact that instruction gave no further teaching input in this direction.

The contrary was true with respect to the concept of pressure. The whole instructional approach including representations on a computer screen was based on this concept at that time. The newer versions of the instructional approach include representations of current and resistance on the screen, compare Goldberg et al (1994). The special feature of the intermediate conception "pressure" of Lynn is also strongly determined by her prior conceptions and the former intermediate conceptions: The most stable element in her conception of pressure is a rule high at negative, normal in the bulb, and low at positive, her former development of the intermediate conception "it needs the positive and the negative". So, every time when it comes to a circuit which is not closed, for instance, at the positive, she misses the attracting forces and therefore gets into difficulties. She has similar difficulties when discussing several batteries in series when suddenly the connecting point between the batteries is related to normal. By working hard on own ideas about a pressure diagram with this circuit and the final feedback diagram she starts to overcome this absolute view of pressure and replacing it by a relative view of pressure difference. Teaching input here perhaps has some deficiencies:

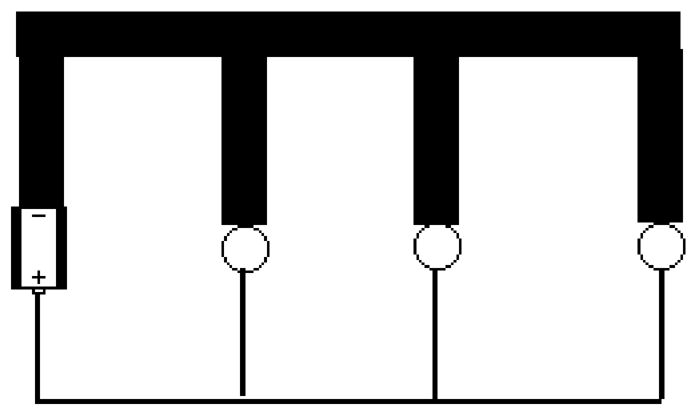
- It should provide simple circuits which focus on pressure differences, such as open circuits or circuits with more than one battery.
- It should provide opportunities for intuitive thinking about pressure with terms like "build-up" and "release" of pressure, helping students with two important pieces of information: first, students should know that an open end is compared to a closed hose (not to an open hose) and second, that pressure is always constant along a good wire (see next page).

Similar pieces of teaching information would be needed with the following items:

- pressure is not released ("spit out") at an open end
- it can be build up from negative if there is no release
- attraction from positive is resulting in "low pressure"
- pressure is not always "high" at negative of a battery and "low" at positive. A battery creates a pressure difference between the ends, e.g. "high" to "low" or "normal" to "2xlow" or "2xhigh" to "normal". It works as a "pressure booster".

One of these pieces of information is explicitly stated in a new version (1994) of F. Goldberg's "Powerful ideas for electric circuits":

Electric pressure in good conductors: The electric pressure has approximately the same value everywhere within all copper wires directly connected together. (This is also the case for other conductors with negligibly low resistance.)



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