BMS / WIJSB

TNW / CSE

UNIVERSITY OF TWENTE.

Learning electrochemistry through scientific inquiry
Conceptual modelling as learning objective and as scaffold

Action Research Project – Embedding, Status & Outlook

Presentation for EDU-lunch meeting – 1 March 2022

Mieke Boon – Arturo Susarrey Arce – Mariana Orozco

Overview

Conceptual Modelling

- Scientific Thinking and Reasoning
- Conceptual Modelling in Engineering Science Education

Action Research Project

Pedagogical Intervention
→ Case Study CSE M4

- Tapping on ideas of Inquiry-Based Learning
- Guided by the use of Conceptual Modelling

Educational Research
→ Case Study CSE M4

- Explorative
- Descriptive
- Evaluative

Introduction & Embedding

Mieke Boon

Challenges of Engineering Science Education

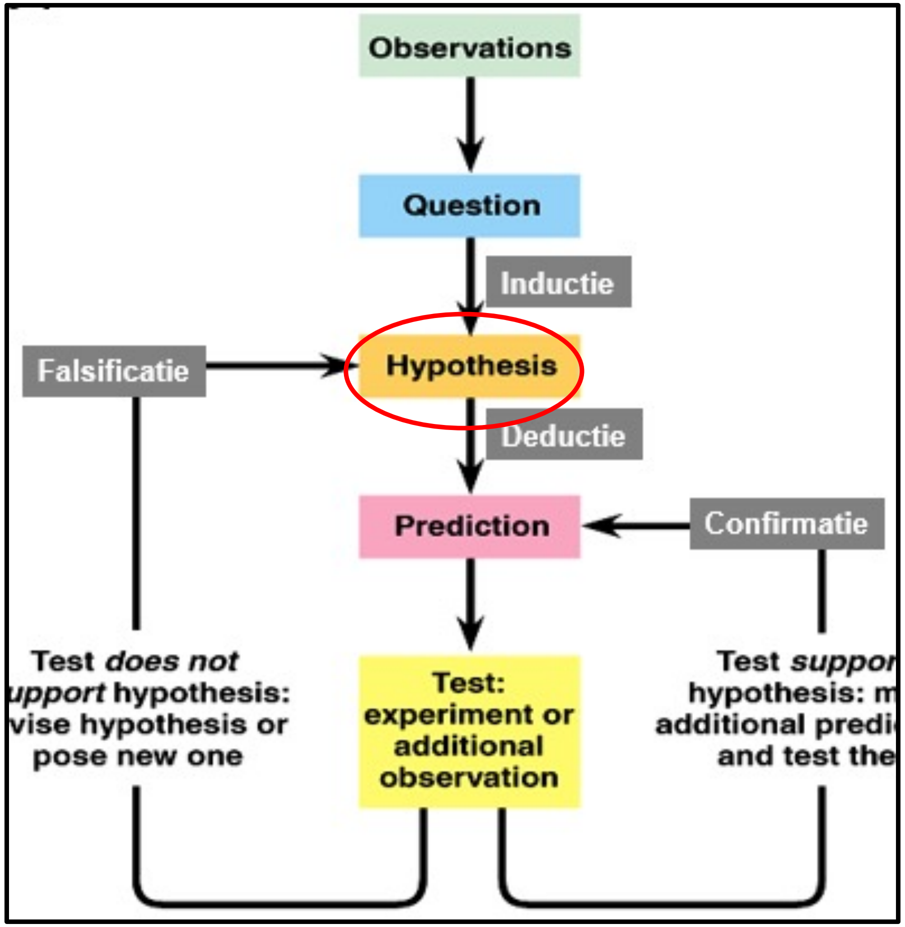
- How to teach scientific reasoning (including critical thinking) in real problems?
  - Teachers feel: students' **scientific thinking & reasoning** could be improved
  - Students have difficulties to **understand scientific theories** (e.g., electrochemistry)
  - Students have difficulties **to apply scientific theories** in real problems (e.g., developing a measurement technique)

- How do we teach scientific research in engineering science education?
  - We often use 'traditional' vocabulary **focusing in (testing) hypotheses** – as expressed in 'traditional' **scientific method**

UNIVERSITY OF TWENTE.

Scientific method

Empirical cycle (hypothetical deductive method)



UNIVERSITY OF TWENTE.

Challenges of Engineering Science education

- How to teach scientific reasoning (including critical thinking) in real problems?
  - Teachers feel: students' **scientific thinking & reasoning** could be improved
  - Students have difficulties to **understand scientific theories** (e.g., electrochemistry)
  - Students have difficulties **to apply scientific theories** in real problems (e.g., developing a measurement technique)

- How do we teach scientific research in engineering science education?
  - We often use 'traditional' vocabulary **focusing in (testing) hypotheses** – as expressed in 'traditional' **scientific method**
  - But **how do we get a hypothesis**?
    And how is hypothesis relevant to Real "**Problem – Solution**"?
  - Is this *hypothesis focused* vocabulary helpful?
    Does it **reflect what we *do* in scientific research**?

- How can we teach differently?
  - Shift from *products* of science (theories, tested hypotheses) to *processes of doing* scientific research

In EngSc education:
Shift from products to process of scientific research (also in teaching theories in Electro-Chemistry) → How?

- Some characteristics of (theory) education
  that make it difficult for students to understand the material and to think for themselves:
  - Connection between **theory (esp. scientific concepts and laws)**
    and concrete observations and experiences (e.g., in lab experiments) remain hidden.
  - => Explain and show how scientific researchers 'invent'
    scientific concepts (often threshold concepts) and laws
    by reconnecting with experimental findings, measurement apparatus, observed data,
    interpretation of data (conceptual and mathematical), assumptions, etc.
  - => Explain and show how scientific researchers reason and call this **modelling**
  - Scientific researchers are **modelling** all the time (rather than testing hypotheses).

UNIVERSITY OF TWENTE.

Modelling as a core activity in *producing* and *using* scientific knowledge about a concrete problem → What is model & modelling?

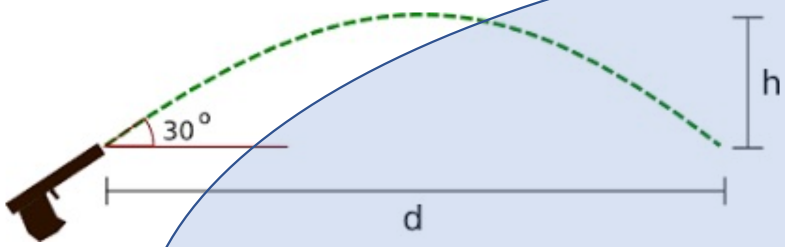
- **Scientific thinking / reasoning** starts with Conceptual Modelling:
  - When observing a phenomenon or problem, scientific researchers try to make a 'story,' e.g., a story that 'describes' or explains the phenomenon.
  - This 'story' is the conceptual model.
  - The 'description' of the phenomenon already makes use of **scientific concepts** students are not familiar with

    => Making the story already involves interpretations making use of your background knowledge.
    Here we often already loose our students.

Conceptual modelling

High-school level: Conceptual modeling precedes mathematical modeling

Example in physics



Assignment: Calculate the trajectory of the bullet that leaves the cannon with a velocity v.

Conceptual modelling (uses concepts from the discipline):

- Explosion of the gunpowder in the gun causes a force on the bullet.
- The force causes the bullet to accelerate.
- Suppose the bullet leaves the gun with velocity v.
- If no force is acting, the bullet will move straight ahead with uniform speed.
- Gravity acts on the bullet and pulls the bullet downwards.
- I neglect the force exerted by the air resistance. The bullet will therefore move in an arc and eventually fall to the ground.

Based on this **conceptual model**, a **mathematical model** can be constructed using Newton's laws.

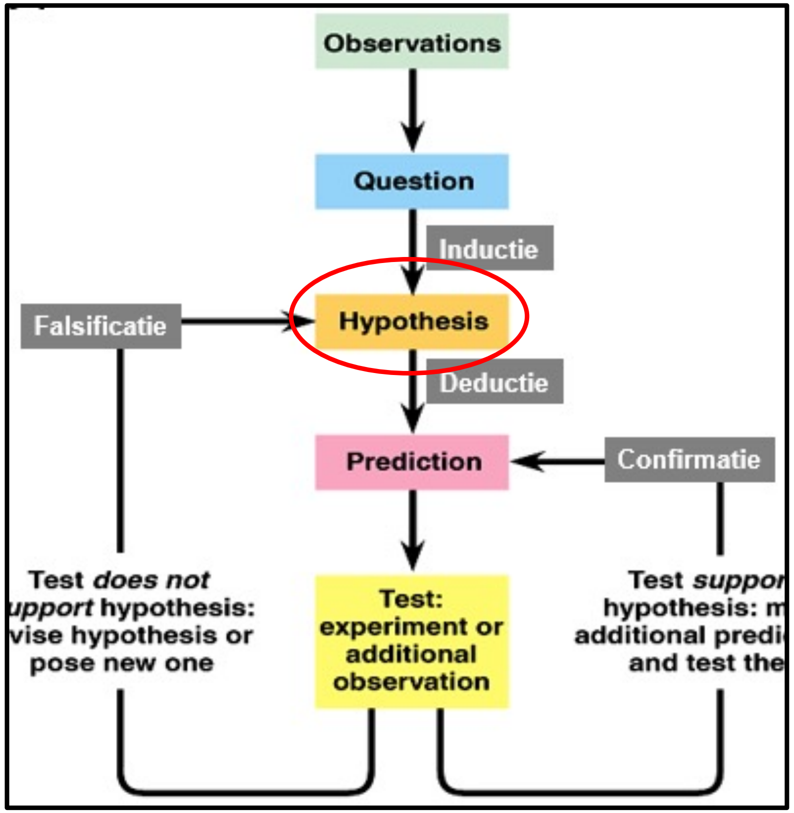
Modelling as a core activity in *producing* and *using* scientific knowledge about a concrete problem → What is model & modelling?

- **Scientific thinking / reasoning** starts with Conceptual Modelling:
  - When observing a phenomenon or problem, scientific researchers try to make a 'story,' e.g., a story that 'describes' or explains the phenomenon.
  - This 'story' is the conceptual model.
  - The 'description' of the phenomenon already makes use of **scientific concepts** students are not familiar with
    => Making the story already involves interpretations making use of your background knowledge.
    Here we often already loose our students.
  - => Explain that these **scientific concepts** have an intelligible physical meaning **and** are connected to (and detectable by) what is measurable (otherwise they are useless).
  - In scientific research, conceptual modelling usually involves a **set of questions to construct the model**. They provide the **ingredients** that go into the model.

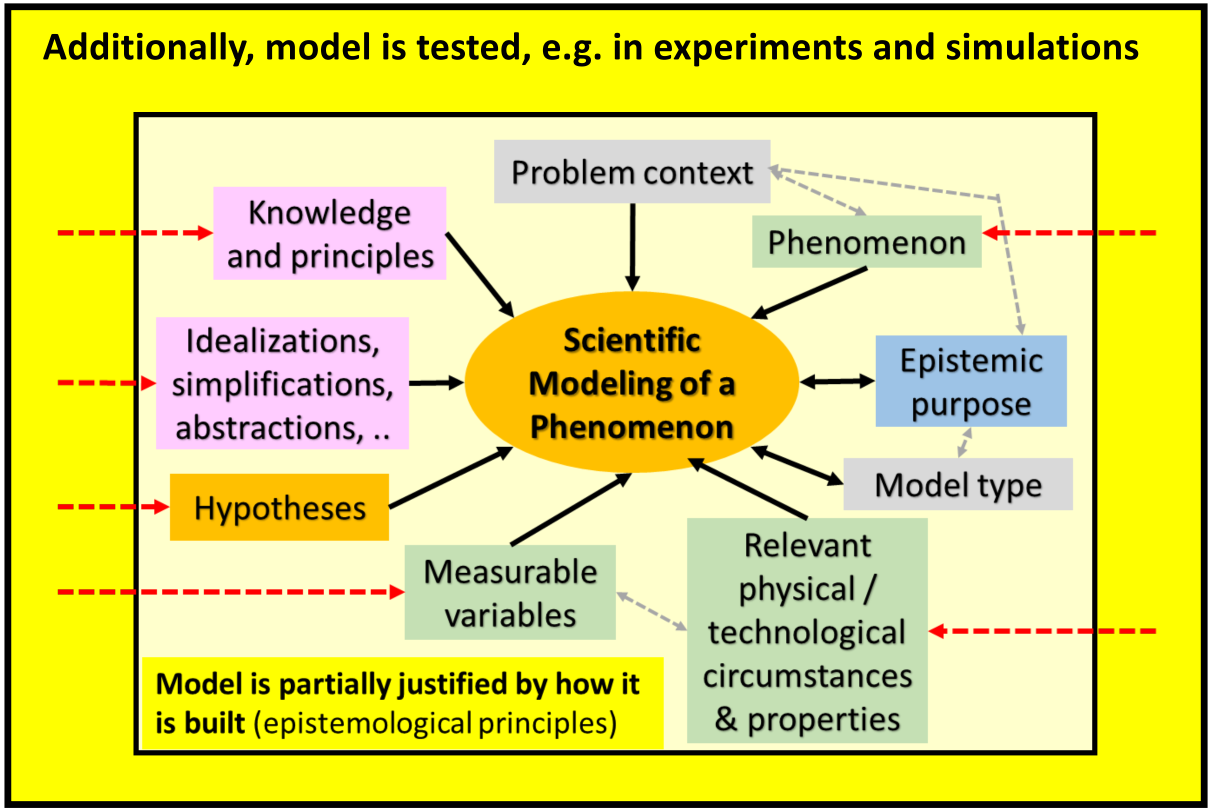
UNIVERSITY OF TWENTE.

Scientific method

HD method in natural sciences



B&K method for (re)constructing (scientific or engineering) models



Modelling as a core activity in *producing* and *using* scientific knowledge about a concrete problem → What is model & modelling?

- **Scientific thinking / reasoning** starts with Conceptual Modelling:
  - When observing a phenomenon or problem, scientific researchers try to make a ‘story,’ e.g., a story that ‘describes’ or explains the phenomenon.
  - This ‘story’ is the conceptual model.
  - The ‘description’ of the phenomenon already makes use of **scientific concepts** students are not familiar with => Making the story already involves interpretations making use of your background knowledge. Here we often already loose our students.
  - => Explain that these **scientific concepts** have an intelligible physical meaning **and** are connected to (and detectable by) what is measurable (otherwise they are useless).
  - In scientific research, conceptual modelling usually involves a **set of questions to construct the model**. They provide the **ingredients** that go into the model.
  - => **How is the model tested?** First, it must meet criteria such as internal logical consistency, internal coherence, consistent with existing knowledge, intelligibility, relevant and adequate in view of its epistemic use (and NOT completeness!), … Second: experimental tests.
  - A conceptual model can be the basis for experiments or mathematical model.

UNIVERSITY OF TWENTE.

Is this relevant to teaching theories?

- How to teach scientific reasoning (including critical thinking) in real problems?
  - Teachers feel: students' **scientific thinking & reasoning** could be improved.
  - Students have difficulties to **understand scientific theories** (e.g., electrochemistry)
  - Students have difficulties **to apply scientific theories** in real problems (e.g., developing a measurement technique).

- Core messages for education in CSE:
  - Students' understanding of theories may improve by connecting with observations, experiences (in the lab), and 'ways of scientific reasoning' that led to scientific concepts and laws.
  - The B&K method of (conceptual modelling) is a systematic description of how scientific researchers model a phenomenon or problem – i.e., the B&K method points out core questions by which we 'think around' and gather information ('ingredients') when modelling.
  - In education (and scientific thinking) this method can support students in two ways:
    a) learning to construct a new model (e.g., a model that 'describes' or explains a phenomenon),
    b) learning to reconstruct an existing model (e.g., to explain the model of an electrochemical phenomenon).

References

How philosophical beliefs about science affect science education in academic engineering programs: The context of construction [copy available on request]
Accepted for Publication Dec 2021 *Engineering Studies*
Mieke Boon

Epistemological and educational issues in teaching practice-oriented scientific research: roles for philosophers of science | SpringerLink
January 2022 *European Journal for Philosophy of Science*
Mieke Boon, Mariana Orozco, Kishore Sivakumar

Scientific Methodology in the Engineering Sciences.
November 2020. In: *The Routledge Handbook of the Philosophy of Engineering:* Chapter 6, Publisher: Routledge
Mieke Boon

4TU CEE links of Educational Innovation:
https://www.4tu.nl/cee/innovation/project/2778/developing-higherorder-academic-skills-in-engineering-education.-focus-on-biomedical-engineering (includes video lecture)

https://www.4tu.nl/cee/innovation/project/2781/learning-electrochemistry-through-scientific-inquiry-conceptual-modelling-as-scaffolding-and-learning-objective-in-chemical-science-engineering-cse-programme

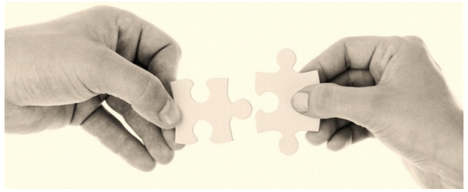
UNIVERSITY OF TWENTE.

Pedagogical Intervention

Arturo Susarrey Arce

Academic Thinking...

Chemical Science and Engineering



CSE – Research phase | **CSE – Conceptual Modelling**

Assignment starts (e.g., redox reaction + electricity)

CSE – Research phase

Guidance: Prior knowledge is provided within the lab manual to narrow down the goal of the lab practice

1. Observation
2. Hypothesis
3. Experiment
4. Formulating a model based on experiments
5. Experimental testing of a theory

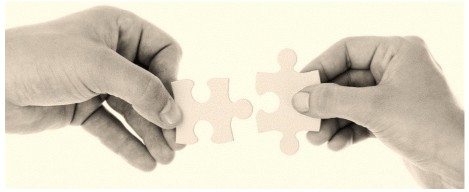
CSE – Conceptual Modelling

Guidance: the topic is provided with keywords (e.g., redox reaction + electricity) + information about chemicals and experimental set-up

1. Observation
2. The what…?, the why…?, and the how…?
3. Interpretation of the problem from an angle…
4. Description of the model based on CM…
5. Then, ***CSE – Research phase*** … 3., 4., & 5.

UNIVERSITY OF TWENTE.

Academic Thinking...



Chemical Science and Engineering

Assignment starts (e.g., redox reaction + electricity)

Guidance: Prior knowledge is provided within the lab manual to narrow down the goal of the lab practice

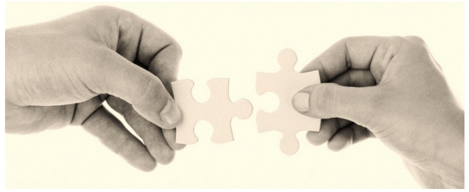
1. Observation
2. Hypothesis
3. Experiment
4. Formulating a model based on experiments
5. Experimental testing of a theory

Guidance: the topic is provided with keywords (e.g., redox reaction + electricity) + information about chemicals and experimental set-up

1. Observation
2. The what…?, the why…?, and the how…?
3. Interpretation of the problem from an angle…
4. Description of the model based on CM…
5. Then, ***CSE – Research phase*** … 3., 4., & 5.

Experimental phase with various research questions from the physical phenomenon

Academic Thinking...



Chemical Science and Engineering

Assignment starts (e.g., redox reaction + electricity)

Guidance: Prior knowledge is provided within the lab manual to narrow down the goal of the lab practice

1. Observation
2. Hypothesis
3. Experiment
4. Formulating a model based on experiments
5. Experimental testing of a theory

Guidance: the topic is provided with keywords (e.g., redox reaction + electricity) + information about chemicals and experimental set-up

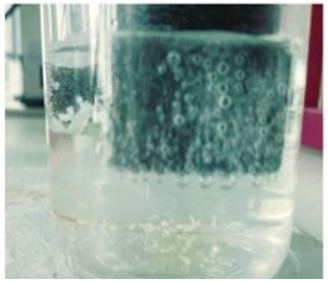
1. First thoughts and experimental design by students
2. Guidance to students with LAs to stream down their thoughts about the phenomenon under study
3. Guidance on the experimental setting that could answer the phenomenon
4. The first conceptual model is developed, experimental phase starts

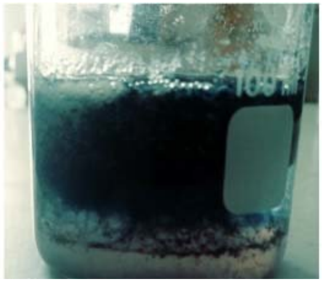
Example: redox reaction + electricity

Chemical Science and Engineering

CSE – Experiments start with potential observations (expectations) and lots of questions

Observation: *the existence of chemical reactions and electricity? // a colour change??*





Why a colour change? // would it be due to molecules?

Why electron transfer causes a colour change?;

What type of reactions exist that can transport electrons?;

*How does it occur, and what else **can I measure**?*

UNIVERSITY OF TWENTE.

Example: redox reaction + electricity

Chemical Science and Engineering

1. CSE –

pH meter

beaker

Hot stirrer

Magnet

pH buffer solutions

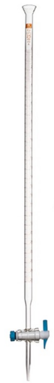
Chemicals:

M $K_4Fe(CN)_6$
KNO_3
NaOH
H_2SO_4
Buffers

Pt electrode

Multimeter

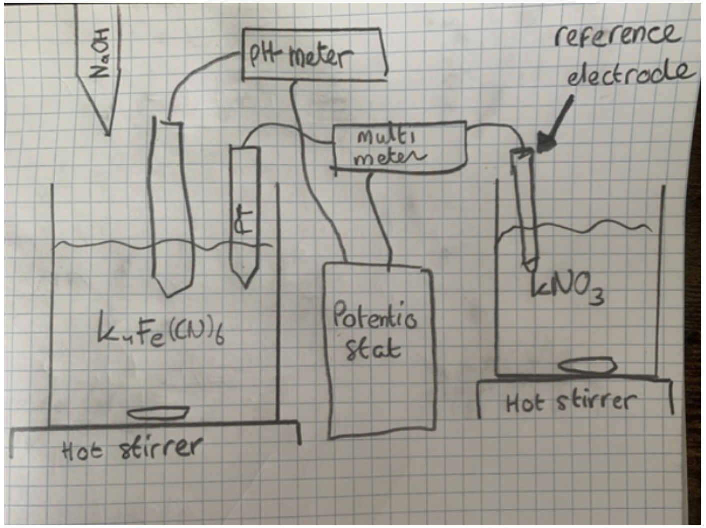
Reference electrode



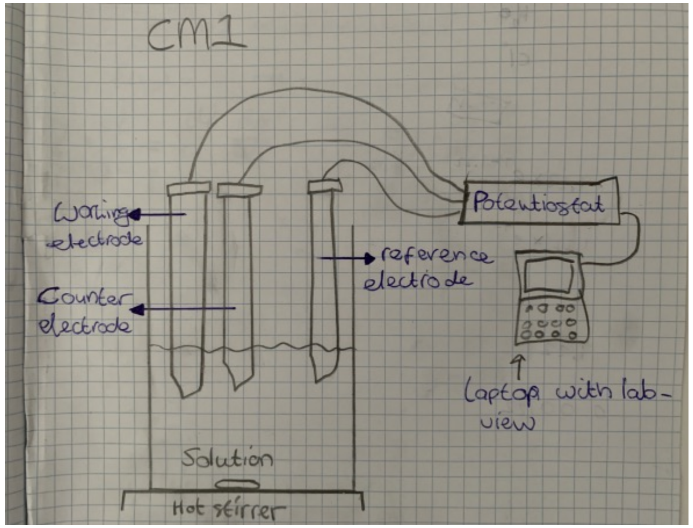
Burette

Potentiostat

CM0:

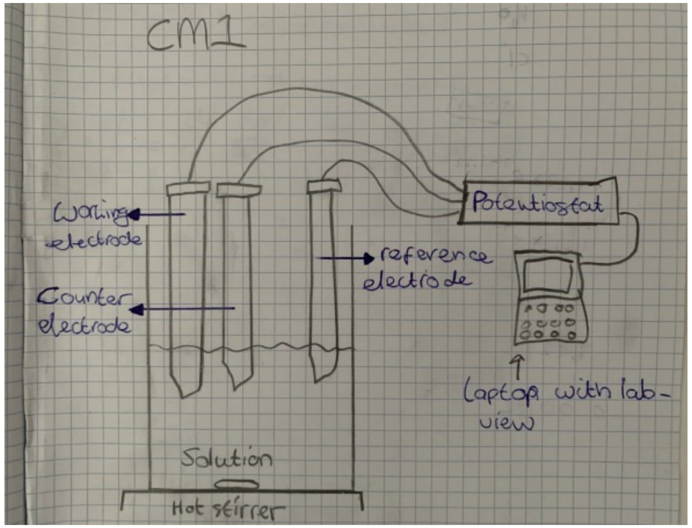


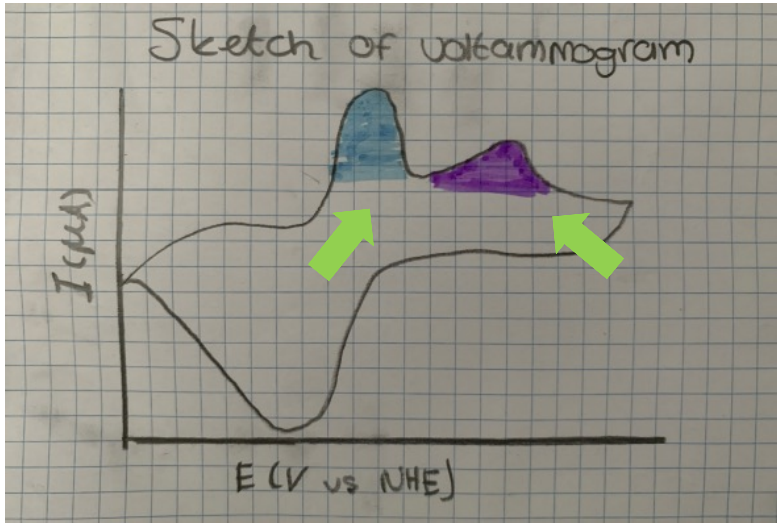
CM1:



UNIVERSITY OF TWENTE.

CM1:





Conclusions:

1. Students identified a chemical reaction by looking at the redox peaks
2. Diffusivity constant estimated
3. Effect of pH and electrolyte determined
4. Effect of T on the overall redox peaks and reaction diffusivity determined

…

To date…

Chemical Science and Engineering

CSE –

Phase 1 – started last year (2021): **electrochemistry meets CM,** and **students meet CM**

Quote 1 – … students find it challenging because no information is given…

Quote 2 – …inspirational, challenging, rewarding…

Quote 3 – …thinking like a scientist…

Phase 2 – improvements are necessary (2022)

Phase 3 – refined version is expected (2023)

Educational Research

Mariana Orozco

Research Purpose

Re-design, implement and evaluate a new course to contribute to students' building deep insight into electrochemical concepts & phenomena, and promote their scientific reasoning & attitude.

Approach → Action Research

- Pedagogical intervention → joint effort of teachers & researchers from TNW & BMS
  - Tapping on ideas of inquiry-based learning
  - Guided by the use of conceptual modelling
- Educational research → explorative, descriptive, evaluative
  - Intervention study
  - Phenomenological approach

Use of qualitative methods of data collection and analysis, seeking description of the phenomenon of learning, focussing on the students, LAs and teachers' experiences.

Research Approach

- Explore
  - Understand how M4-students learn electrochemistry under the pedagogical intervention

- Describe (in an integrative fashion)
  - Behavioural aspects of learning → e.g., indicators of progress in reasoning
  - Assessment results → i.e., process & product evaluation, by LA & teachers
  - Contextual conditions → e.g., sequencing of learning activities, groups working

- Evaluate
  - Find out whether the new approach has any effect (& to what extent)
    - on the near and far-reaching learning outcomes in M4 → using the learning objectives as criteria
    - (on transfer of electrochemical concepts in M5 → terms of mastery of concepts)

UNIVERSITY OF TWENTE.

Theoretical Framework

- Conceptual modelling and the B&K method → overarching (sensitising concepts)
  Boon, M. (2020); Boon, M., & Knuuttila, T. (2009)

- Qualitative differences in learning → overarching (sensitising concepts)
  Marton, F., & Säljö, R. (1976)

- Levels of complexity → analytical framework
  Welzel, M. (1998)

- Recurrent difficulties → analytical framework
  De Jong, O., & Treagust, D. (2002)

Theoretical Framework – Full references

- Conceptual modelling and the B&K method

Boon, M. (2020). Scientific methodology in the engineering sciences. In D. P. Michelfelder & N. Doorn (Eds.), *The Routledge Handbook of the Philosophy of Engineering* (1 ed.). New York: Routledge.

Boon, M., & Knuuttila, T. (2009). Models as Epistemic Tools in Engineering Sciences: A Pragmatic Approach. In A. Meijers (Ed.), *Philosophy of technology and engineering sciences. Handbook of the philosophy of science* (Vol. 9, pp. 687-720). North-Holland: Elsevier.

- Qualitative differences in learning

Marton, F., & Säljö, R. (1976). On qualitative differences in learning I: Outcome and process. British Journal of Educational Psychology, 46, 4-11.

- Levels of complexity

Welzel, M. (1998). The emergence of complex cognition during a unit on static electricity. International Journal of Science Education, 20(9), 1107-1118.

- Recurrent difficulties

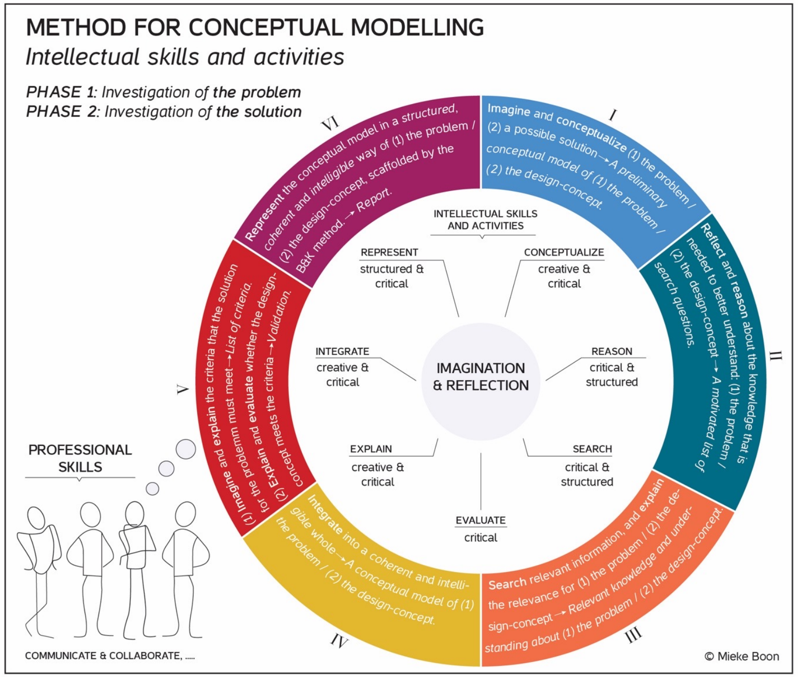
De Jong, O., & Treagust, D. (2002). The teaching and learning of electrochemistry. In J. K. Gilbert, O. De Jong, R. Justi, D. Treagust, & J. H. Van Driel (Eds.), Chemical Education: Towards Research-Based Practice (pp. 317-337). Dordrecht: Kluwer Academic Publishers.

UNIVERSITY OF TWENTE.

Conceptual Modelling and B&K Method

Boon, M. (2020); Boon, M., & Knuuttila, T. (2009)

- CM as **learning objective** → intellectual skills
- CM as **scaffold** → guided way of reasoning



Three phases → 1, 2a, 2b

- Own steps → I to VI
- Same skills
  - Overarching → imagination & reflection
  - Activities → conceptualise, reason, search, evaluate, explain, integrate, represent
  - Qualifiers of activities → critically, creatively
- Own intermediate products and final outputs

UNIVERSITY OF TWENTE.

Conceptual Modelling and B&K method

Phase	Process	Outputs
1. Framing the phenomenon one wishes to investigate	**Steps I to VI** (incl. intermediate products) particular to each phase **Overarching skills:** imagination & reflection **Activities:** conceptualise, reason, search, evaluate, explain, integrate, represent **Qualifiers of activities:** critically, creatively **Guided by B&K method:** series of reflection questions for awareness, vocabulary, and understanding	• CM_0 of the phenomenon • Motivated list of search questions, and identification of relevant knowledge • List of criteria to appraise the CM_1
2a. Designing how to investigate the phenomenon		• CM_1 of the experimental design-concept (EDC), including the experimental setup • Motivated list of further search questions • List of criteria to appraise the CM_2
2b. Carrying out the experiment to interpret the results, and formulate plausible explanations		• CM_2 of the explanation • Motivated list of further search questions

Qualitative Differences in Learning

Marton, F., & Säljö, R. (1976)

- Differences in learning are best observed in connection to the **content**, and in both the **process** and the **outcomes** of learning

- Consider the students' →
  - Prior conceptions of the key concepts at stake
  - Evolving conceptions of those concepts
  - Evolving task conception (its goal and content)
  - Functional differences in process

Levels of Complexity

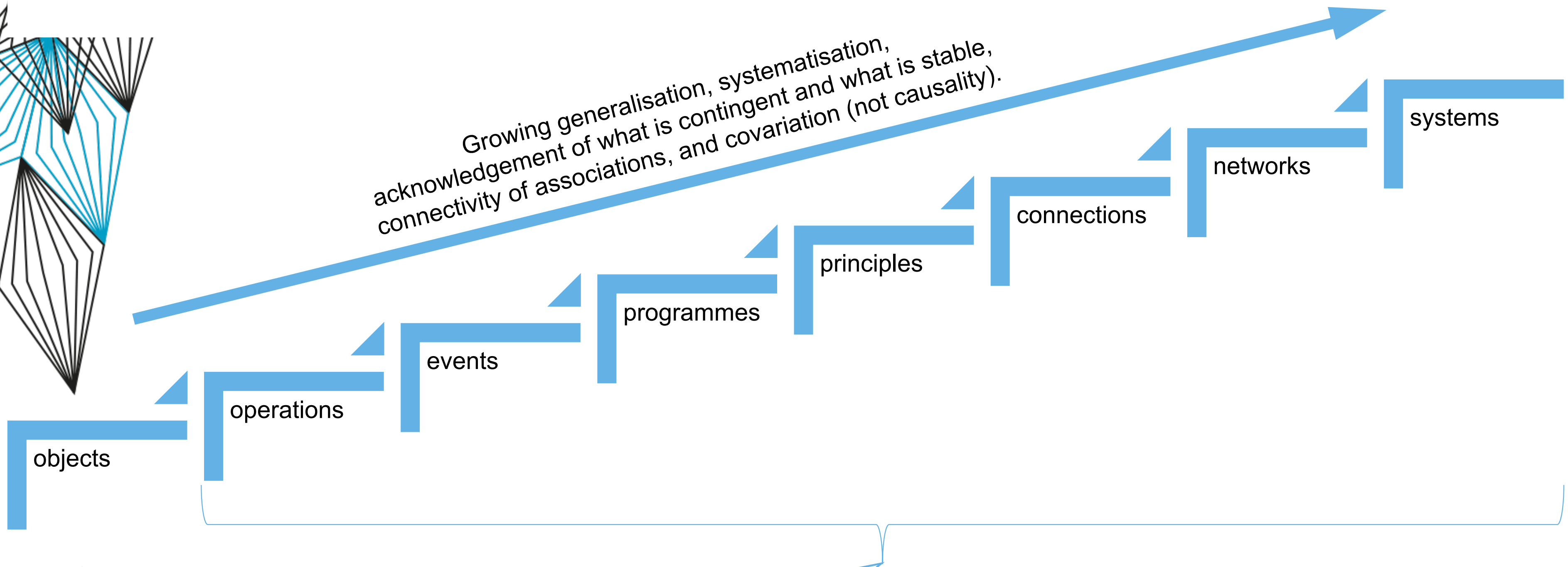
Welzel, M. (1998) with modifications

- Original heuristics on levels of complexity → 10 cats. denoting increasing complexity

- Our use of this framework
  - Grasping in what ways one category is more complex than the preceding
  - Grasping what it takes to move from one category level to the next higher
  - Operationalisation into our empirical context → using actual research data
  - Modifications:
    - Cat. ‘objects’ broadened to include any materials
    - Cat. ‘aspects of variations’ added to attend to students’ qualifiers of events and other relations
    - Cat. ‘purpose’ added to attend to students’ practical reasoning

UNIVERSITY OF TWENTE.

Levels of Complexity



Objects & other materials

- their aspects → their properties
- their purposes!

Covariations of aspects and properties of objects and materials

- extent/size often qualified qualitatively and/or quantitatively
- under certain conditions

Recurrent Difficulties

De Jong, O., & Treagust, D. (2002)

- Origins of the teaching and learning difficulties:
  - Rote application of concepts and algorithms
  - Use of multiple definitions/meanings (stemming from different contexts*)
  - Use of multiple models or of hybrid models
  - Wrong interpretations of language
  - Too early connection of labels to meaning
  - Misleading analogy
  - Attribution → our addition

- *Distinction of contexts
  - Based on a historical analysis on ‘electrochemical concepts and their meaning in context’ → the phenomenological, the particulate, the measurement, and the thermodynamic contexts
  - This analysis is not to fragmentate what the Conceptual Modelling approach aims to unite (by organising it coherently), but to understand the epistemological difficulty and complexity that electrochemistry represents for students, teachers and researchers

Preliminary Findings

LOCX - Levels Of CompleXity (1/2)

- Students 'skip' several levels (esp. in practicum on Daniell cell)
  - E.g., passage from objects to events
  - Rather than 'true discovery', the students
    (a) appeal to prior knowledge and/or
    (b) by-pass the instructional sequence by searching on the Internet

- Much centrality of objects and materials (esp. in practicum on voltammetry), even more than the phenomenon under study (which is often not made explicit)

- It seems beneficial for the students' reasoning/comprehension to mention and actually consider the purpose or function of the materials in the experimental setup.
  - They often do this spontaneously
  - Several difficulties seem to stem from unclear purpose (rote use of statements)

Preliminary Findings

LOCX - Levels Of CompleXity (2/2)

- The students seldom go beyond the level of 'events'
- No growth observed over time (neither within each experiment, nor between experiments), i.e., students seem to stagnate at a relatively low level → plausible explanations:
  - Not getting the opportunity to grow…
  - Not taking the opportunity to grow…
- Beyond attending to whether there is a covariation or not, students often pay attention to aspects of covariations
  - Mainly in terms of quality and quantity (rather than directionality)

Preliminary Findings

KRD - Known Recurrent Difficulties (1/3)

The KDR categories allow to think about plausible causes of difficulties
→ to understand the cause, we need to understand the disciplinary content
→ but we do not focus on content analysis of misconceptions

- Rote application of concepts and algorithms
  - The biggest category by far
  - Rote application gives a false sense of understanding
  - Often use of concepts, and even full statements without grasping any meaning
  - Use of algorithms without grasping their meaning (e.g., their basis and implications), often attempting to replace the explanation of a phenomenon → tendency to ‘apply’, ‘confirm’, ‘satisfy’ equations

- Mixed meanings
  - Use of multiple definitions or meanings → seldom observed so far
  - E.g., ‘equation’ used to mean both ‘mathematical equation’ and ‘chemical formula’, leading to inappropriate interpretation of lab results

Preliminary Findings

KRD - Known Recurrent Difficulties (2/3)

- Hybrid models
  - Confusion of distinctive models in one → different ‘contexts’, purposes, explanatory routes
  - E.g., “the slope is constant and at some point the slope starts changing again […]
    that's where the actual reaction starts happening again”

- Misinterpret language
  - Seldom observed so far
  - E.g., ‘scanning’ understood as ‘monitoring, measuring, reading’,
    while ‘scanning’ in voltammetry is used to denote the deliberate variation of a potential difference at a constant rate

- Too early labelling
  - Too early connection of labels to meaning observed a few times
  - E.g., using the terms ‘cathode’ and ‘anode’ without understanding what happens at each electrode,
    as if the very name would convey some meaning

Preliminary Findings

KRD - Known Recurrent Difficulties (3/3)

- Misleading analogy
  - Not observed so far
- Attribution
  - Groundless or wrong attribution of effect (e.g., causality, mediation, interaction, contribution)
  - E.g., “increasing the concentration of reductor results in a lower voltage *because* the concentration is in the denominator of the Nernst equation”

Preliminary Findings

QuaLD - QuaLitative Differences in terms of Content

- Prior and evolving conceptions cannot be extracted from our data (excepting perhaps a few scattered instances) → this would require…

- The conceptions of the task are more explicitly discussed:
    - Instances of LAs clarifying the purpose of the task and suggesting directions
    - Instances of students acknowledging some aspect of the task in conversation with the LAs
        - Students seem concerned about not grasping what is expected from them and about the complexity of the task
        - Students tend to reduce complexity in some inappropriate way

- Functional differences in the process are not observed
→ this would require…

UNIVERSITY OF TWENTE.

Preliminary Findings

CM - Conceptual Modelling Framework

- The B&K method or not or hardly used (despite explicit reference or not):
  - Lack of identification of the phenomenon of interest
  - Vagueness about the epistemic purpose of the CM
  - Lack of prediction or hypothesis

- Variables are often mentioned, although (almost) invariably in terms of their measurability
  → i.e., at the expense of the distinction between manipulated and controlled variable
  - The students often behave as passive observers of variables that can only be measured, without acknowledging the possibilities to 'play', intervene, manipulate, so to produce a change that they may wish to predict, test, and describe/explain

- Further 'overarching findings' are expected in terms of 'conceptual modelling skill'

Some Recommendations

- Students' conception of the task and believes about their roles
  - Help students to embrace complexity rather than reducing it
    - e.g., praise risk-taking, suggest how to deal with uncertainties
    - e.g., promote the practical reasoning skill to weed-out and let-go → *part of thinking critically!*
  - Request the thorough use of the B&K method
    - awareness → vocabulary → conceptualisation → developing reasoning within and beyond the task
    - convey its importance → e.g., as much as a safety-risk analysis
  - Distinguish 'manipulated' variables from 'controlled' variables
    - de-emphasise mere 'measurement' and 'observation' to aim for a more active intervention
    - predict, test scenarios (to further explain, calculate, and connect to prior knowledge) → *part of thinking creatively!*
- Building on previous for further growing
  - Consider reducing the number of 'different' practicums
    to allow for a second lab experience around the same topic
  - Emphasise the connections between 'different' practicums
- Collaborative learning
  - Introduce peer review of (intermediate) products → as a standard best practice
  - Continue investing in the professionalisation of (new) learning assistants
    - key role in students' development through CM-scaffolding and engaging in each others' reasoning

Research Outlook

- Planned research activities
  - Further thematic analysis of the data collected (after theoretical sampling)
  - Perspectives & methods triangulation
    Social Reasoning / Situated Cognition ←→ Conceptual Change (using CNA)

- Challenges
  - Systematisation of analytical steps
  - Feasibility of following the participants in further modules → evaluation of 'transfer'

- Beyond the scope of the project
  - Other modules interested in introducing conceptual modelling

UNIVERSITY OF TWENTE.

Thank you for your attention

Mieke Boon – m.boon@utwente.nl

Arturo Susarrey Arce – a.susarreyarce@utwente.nl

Mariana Orozco – m.orozco@utwente.nl

UNIVERSITY OF TWENTE.