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ASSESSMENT TASKS TO MEASURE SYSTEMS THINKING AND CRITICAL THINKING IN ORGANIC CHEMISTRY

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Abstract: Humans of 21st century should possess higher order thinking skills such as critical thinking and systems thinking skills. Development and assessment of students' critical thinking and systems thinking skills should be a crucial objective for every teacher. However, only relatively recently the scientists proposed models for the development of items to measure systems thinking and critical thinking. Herein are presented theoretical issues regarding systems thinking and critical thinking, as well as examples of items which could be used to assess systems thinking and critical thinking, on the topic of manipulation of functional groups in organic chemistry.

***Keywords*:** assessment of critical thinking, assessment of systems thinking, functional group manipulations in organic chemistry

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Assessment of higher order thinking skills

In order to meet the challenges of 21st century, one must possess skills such as formulating arguments, problem-solving skills, critical thinking, creativity, communication, collaboration, systems thinking, as well as self-management ability, flexibility, adaptability, self-development ability.[1] Higher order thinking skills (HOTS) could be defined: a) as related to transfer, b) in terms of critical thinking and c) as related to problem solving.[2] The necessity of developing HOTS was reflected in the learning taxonomies, which are used to categorize instructional objectives and assessment in different levels of complexity.[2] Higher order thinking skills are presented at the top end of the cognitive taxonomies.[2-4] A number of studies showed that developing and assessing HOTS increases students' cognitive outcomes (*e.g.*, reasoning), students' curricular outcomes (*e.g.*, math, science tests), affective outcomes (motivation and attitudes).[2] Brookhart[2] defined a few general principles which should be followed when assessing higher order thinking: a) the students should be presented a material to think about (item stem, resource material, scenarios, etc.), b) the materials should be new to the students, c) when developing items to measure HOTS, the level of difficulty and the level of thinking should be controlled for in an independent way.

Herein are presented information on critical thinking and systems thinking, as well as examples of tasks to assess them, since these skills are considered to be important skills for Chemistry students.[5-7]

Systems thinking

The interest of scientists and educators in topics such as socio-scientific issues and systems thinking has increased lately, top scientists and educators urging for more research on these topics to be undertaken.[6,7] Scientists as well as lay people should consider the possible societal consequences of their actions. Systems thinking is the ability to think holistically, to observe the non-obvious connections between the parts of the system, and to understand why parts of a system act in the way they act.[8] Furthermore, those who possess the systems thinking ability are able to: identify systems, understand systems, predict system behavior, design changes to systems, in order to produce desired effects.[9] Fahmy and Lagowski[10] proposed the systemics perspective in teaching and learning in Chemistry, as a way to promote meaningful learning.[11] They defined systemics or systemic diagrams as 'arrangement of concepts or issues through interacting systems in which all relationships between concepts and issues are made explicit to the learner, using concept map-like representations' [Ref. 10, pp 1079]. The systemic diagrams are different than concept maps. Whereas concept maps have a hierarchical structure and emphasize the linear relationships between concepts, the systemic diagrams are meant to represent closed systems of concepts and all possible relations between these concepts.[10,11] A variety of methods were used for the evaluation of systems thinking: by assessing students' understanding of simple system diagrams, by using the 'think aloud' procedure, interviews, cognitive mapping.[12] Systemic diagrams could be used for evaluation of meaningful learning in Chemistry; they are destined to evaluate a large number of concepts.[12] The systemic assessment questions (SAQs) were introduced by Fahmy and Lagowski[13] and include a smaller number of concepts in their structure than systemics diagrams. The SAQs could have diverse geometric shapes: triangular, quadrilateral, pentagonal, etc.; the clockwise or anticlockwise direction of relationships between concepts must be specified.[10,13] Research regarding systemic thinking in Chemistry classroom focused mainly on systemic thinking assessment.[12,14]

Critical thinking

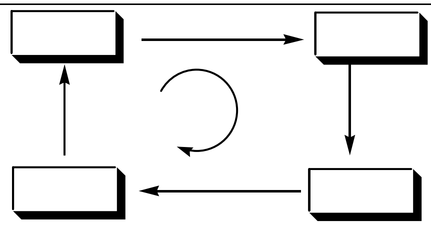
Norris and Ennis defined critical thinking as 'reasonable, reflective thinking that is focused on deciding what to believe or do'.[15] [Ref. 15, pp 3] Critical thinking is an essential skill for scientists and engineers, and it is expected that Science and Engineering students possess this skill upon graduation.[5,16,17] Employers seek graduates who are able to think critically; however, in practice, most of the graduates are deficient in critical thinking.[18] There is a debate between the researchers who believe that critical thinking is a general skill and those who believe that it is subject specific.[19,20] A number of conceptualizations of critical thinking were proposed along the time, by psychologists or subject education specialists.[20] Among the psychologists, Halpern proposed the following components of critical thinking[21] and the author claims that these components could be suitable for all subjects: reasoning, hypothesis testing, argument analysis, likelihood and uncertainty analysis, decision-making and problem-solving. On the other side, chemistry engineering education specialists proposed the following components, specific for chemistry and Chemistry engineering fields: idea generation and prioritization, explaining unexpected results, problem formulation, selecting from among alternatives, analyzing, critiquing, grading.[22] The models regarding the components of critical thinking could be useful when developing items to measure this skill. It was stated that for the assessment of critical thinking skills, a combination of both multiple-choice and constructed answer items should be used.[20] Examples of items to assess critical thinking in Chemistry were published (*e.g.*, Ref. 5 and 22), but to the best of our knowledge, a comprehensive empirical study regarding the assessment of critical thinking skills in Organic Chemistry is lacking. Among the instructional methods used for fostering critical thinking in Chemistry are: work integrated learning, practical activities, inquiry, gamification, flipped lectures, writing exercises.[23]

Examples of items to measure critical thinking and systems thinking

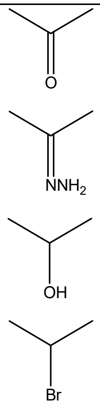
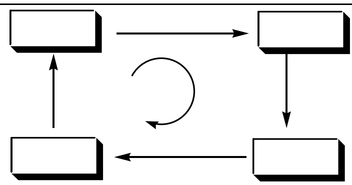
Functional group manipulations is a key skill for organic chemists and hence this topic was selected for the development of items to measure critical thinking and systems thinking. The models for items presented here could be especially useful for Chemistry teachers who are interested in fostering and assessing students' higher order thinking skills.

Examples of SAQs to assess systems thinking (developed by using the model of Fahmy & Lagowski)

SAQs regarding functional group syntheses and transformations are presented in Schemes 1-2. The students are expected to fill in the column B, by using compounds and rection conditions from columns A and C. The answers are provided in Annex.

A	B	C
CH_3-CH_3 CH_3CH_2OH CH_3CH_2Br CH_3CH_2OTs		aq KOH Br_2/hν TsCl $LiAlH_4$

Scheme 1: SAQ regarding the transformation of an alkane intro an alcohol and the backward transformation.[24]

A	B	C
		CrO_3, H_2SO_4 Br_2 / hν H_2O/dioxane/[bmim][BF_4] (8:5:3), 100^0C NH_2NH_2, base, Δ

Scheme 2: SAQ regarding the transformation of a haloalkane into the corresponding ketone and the backward transformation.[24, 25]

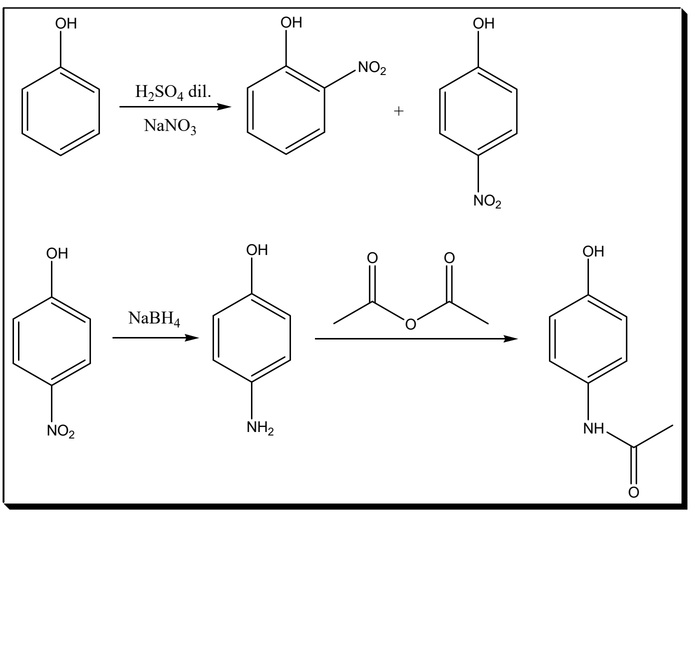
Items to assess critical thinking (developed by using the model of Brent & Felder)

Underneath are presented examples of items to measure critical thinking abilities. The topic is functional group transformations for the synthesis of paracetamol, by using different methods.[26-30]

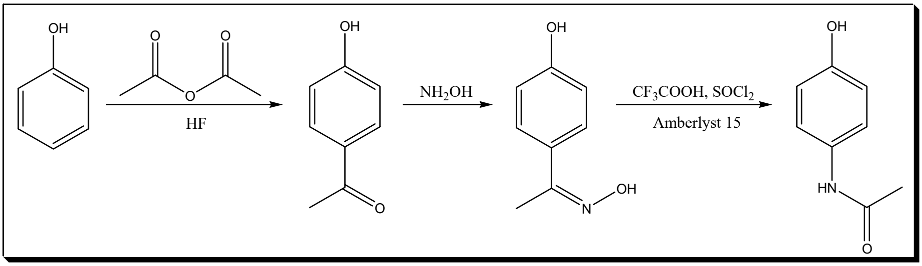
Items stem

Below are written the reaction sequences for the synthesis of paracetamol *via* different methods.

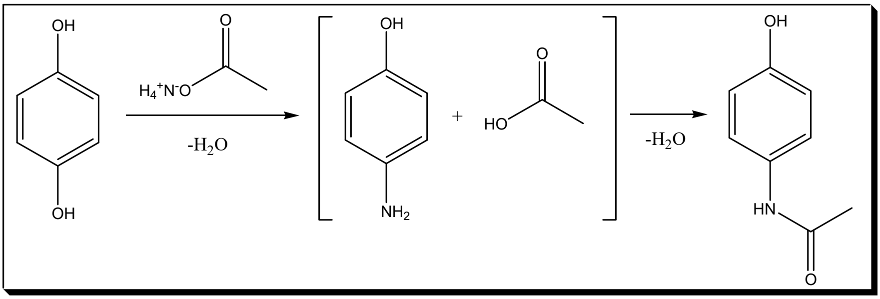
Method 1:



Method 2:



Method 3:



1. **Idea generation and prioritization**

What flaws or possible risks could involve the synthesis of paracetamol by method 1? List at least three, compare their importance and provide a ranking.

2. **Explaining unexpected results**

Look at the first step for the synthesis of paracetamol depicted in method 2, and read the practical procedure for this step (Ref 30). Explain why the acetylation of phenol leads to the synthesis of 4'-hydroxyacetophenone in 96% yield and does not lead to the synthesis of a mixture of ortho- and para-substituted phenol.

3. **Problem formulation**

Make up and solve a problem involving the material covered on the topic *Functional Groups Transformations*, regarding the chemical transformations of phenols.

Nota bene: It is expected that you design an item to measure analysis and / or critical thinking.

4. Selecting from among alternatives

In the items stem were presented 3 methods for the synthesis of paracetamol. Select the one you find the most cost-efficient and justify your answer.

5. Analyzing

Compare and contrast the 3 methods presented above for the synthesis of paracetamol.

6. Critiquing

Read and critique the article *How Efficient Is My (Medicinal) Chemistry* (Ref 30), regarding the „greening" methods for the synthesis of paracetamol.

7. Grading

At item 5, one student from the last year answered:

"All 3 methods have in common the synthesis of paracetamol and the utilisation of acetic acid for its synthesis."

Grade this answer.

Concluding Remarks

Studies[31] have shown that teachers benefit from training sessions on how to foster HOTS in students. The theoretical information and the models for the items presented here could be used by teachers as a first step in their endeavors to improve their skills on how to foster and evaluate students' HOTS.

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