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Current Situation with University Education in Catalysis: A Helicopter View

Dmitry Yu. Murzin[1,*], Ekaterina S. Lokteva[2]

[1]Åbo Akademi University, Turku, Finland
[2]Lomonosov Moscow State University, Moscow, Russia
*Corresponding author: dmurzin@abo.fi

Abstract Several aspects of education in catalysis in Europe are discussed based on a symposium devoted to education in this field organized within the framework of the European congress on catalysis.

Keywords: *catalysis, education, curricula*

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1. Background

As well-known catalysis is the backbone of the current chemical industry and oil refining, thus education in this area has been always a concern of academia and industry.

European Federation of Chemical Engineering for example recommends [1] minimum requirements for certain subjects and topics of chemical engineering closely related to catalysis. According to these recommendation besides fundamentals of chemical engineering such topics as material and energy balances, thermodynamics, fluid dynamics, heat and mass transfer, separations, bio molecular and biological engineering should be covered.

Strangely enough, if curricula for undergraduate and graduate chemical engineering education in general are a subject of a number of publications including details of the curriculum structure and organization [2,3,4], less attention is paid to education in catalysis.

In fact after browsing the journals devoted to chemical and chemical engineering education only one paper was found where the outline for the course in industrial catalysis was presented [5].

Apparent voids which exist in the information flow between educators in different universities from different continents could be related to the fact that catalysis is a very multidisciplinary field, practiced not only by chemical engineers, but by physical, organic or analytical chemists, as well as physicists.

An attempt to fill the voids in sharing information about education in catalysis at the undergraduate and graduate levels was recently made at the European Congress on Catalysis, held in Kazan in 2015. European Federation of Catalysis Societies somewhat reluctantly at the beginning agreed to arrange a symposium on education in the field of catalysis within the framework of the congress. The symposium to the surprise of the organizers attracted a lot of participants.

The main intention was to discuss various aspects of education in catalysis, including teaching approaches in different parts of the world. Several questions were in the focus of the discussion, including: when to teach catalysis, what to teach and how to do it, what should be the teaching depth and tools and finally is the knowledge of lecturers adequate.

Although presentations were mainly given by various European professors, namely F. Cavani (Bologna, Italy), E. Hensen (Eindhoven, The Netherlands), M. Muhler (Bochum, Germany), D. Murzin (Turku, Finland), M. Skoglundh (Gothenburg, Sweden) input from other continents was also provided through the talks of J. Beltramini (Brisbane, Australia) and C. Jones (Atlanta, USA). Moreover several representatives of the host country V. Lunin (Moscow), V. Bukhtiyarov (Novosibirsk), K. Kharlampidi (Kazan) had a chance to address various aspects of teaching catalysis as a part of classical chemical as well chemical engineering education.

Although the selection might look rather random presenting a snapshot of catalysis education in just a few mainly European countries some interesting patterns became apparently clear.

It might be argued that teaching of catalysis depends on the experience of the teacher and therefore cannot be generalized. Moreover, due to diversity of the job market catalysis is taught as a branch of chemistry, chemical engineering, environmental science, etc., thus the subject of catalysis should be taught just on the basis of teacher' personal experience.

Personal opinion of the authors is that extensive exchange of students within EU at every level (BSc, MSc and PhD) because of a number of exchange programs and a job market, open for graduates coming from different countries, require much better awareness of the situation with education in catalysis across Europe and globally. The main aim of the authors is not to have a detailed and comprehensive overview on catalysis education with extensive analysis and recommendations, but rather to initiate a discussion and exchange of the best practices.

Apparently there is a lack of information about education in catalysis in Europe and at the same time there is a strong need at least in Europe to know who is doing what and how.

2. Catalysis Education Landscape

Higher education in Europe, characterized by a strong theoretical base and typically strong orientation to research, was very much influenced by the so-called Bologna process. The latter had several objectives including among other the following ones: adoption of a system of comparable degrees with two main cycles (undergraduate and graduate), establishment of a system of credits and student mobility. The latter opportunity is extensively utilized by students and one of the authors regularly gives lectures to students, who are coming to Finland just for one or two semesters. A credit should be given to the Erasmus program which is the key to the increased student mobility within EU.

In Europe besides Erasmus mobility programs, mentioned above, there are also Integrated Training Networks as an instrument in education for PhD students; moreover there are also joint doctorate programs. While these programs work successfully act at the European level, they have too low critical mass to have a significant impact on education in catalysis and take things one step further in the direction of a European Master or PhD in catalysis.

In fact, an interesting trend, which was noticeable from several presentations, is that in many European countries such as Finland as well as in the US there is no coordination between universities in terms of the number of courses devoted to catalysts, its content and structure.

For example, a course in heterogeneous catalysis taught at Åbo Akademi University, Turku comprises 56 h lectures and 10 exercises as well as 2 laboratory works. This course is given at the undergraduate level (BSc) to chemically oriented chemical engineers and includes such topics as basic concepts, catalytic materials, catalyst synthesis and characterization, fundamentals of adsorption, reaction mechanisms, catalytic kinetics, mass transfer and heat transfer in heterogeneous catalysis as well as catalytic reactors. Examples of various catalytic processes are presented in another course describing chemical process technology.

Two laboratory works are selected by the students from a number of offered labs in a particular year depending on the research interests of the lecturers and can include for example synthesis of metal modified zeolites, characterization of catalysts by pyridine FTIR, surface area measurements by nitrogen physisorption, determination of metal dispersion by CO chemisorption, and some catalytic reactions using zeolites or supported metals.

Within this main scope of the course the lecturer is very flexible not only with the type of laboratory works and exercises, but also can easily modify the course showing examples from particular research projects or recent literature.

There are three other universities in Finland where education is given to chemical engineers with some courses in catalysis; however, there is no exchange of information regarding education between lecturers.

At the PhD level, countries such as Finland have a system of national graduate schools, thereby providing courses not only to students who are enrolled in those schools but to all those, who desire to take such courses. Intensive courses on a particular topic related to catalysis (for example, catalysis for biorefining) are occasionally organized. PhD programs in chemical engineering require typically that students get 40 credits, which are individually selected and include not only courses, but also exams based on reading textbooks.

Opportunities to take courses on catalysis based on the unifying approach (heterogeneous, homogeneous and enzymatic catalysis) are offered in Germany by several groups of selected universities located in different part of this country. For the universities located in the Ruhr area PhD students in chemistry and chemical reaction engineering have a chance from the dawn of 21st century every second year to take part in an intensive course (9 full days with 7 h of lectures). The course which has typically ca. 35 participants covers heterogeneous catalysis: (mass transport/kinetics; reaction engineering/reactors; synthesis/characterization; acid-/base and redox catalysis; zeolites), homogeneous catalysis (ligands, catalyst recycling, alternative solvents), electro- and photocatalysis as well as biocatalysis (fermentation/enzyme catalysis and biotransformations).

Professors from the Universities of Erlangen-Nuremberg, Stuttgart, Bayreuth, Ulm and Technical University of Munich established a regional cooperation for the local states (Baden-Württemberg and Bavaria) collectively offering a broad and comprehensive education in fundamental aspects and common principles in catalysis. The course encompasses all aspects of catalysis and does not concentrate on specific sub-disciplines in order to exemplify similarities and differences.

PhD students of any field from these states and Switzerland are accepted into this program with the free of charge participation. The course covers the basics (surfaces, bonding, elementary steps, model catalysts, theory of catalytic reactions), heterogeneous catalysis (preparation, characterization; deactivation, types of catalytic reactions); homogeneous catalysis, organocatalysis; asymmetric catalysis, bio- and electrocatalysis; reaction kinetics and transport phenomena and catalytic reactors.

Somewhat similar 5 days courses are organized separately in Leipzig for PhD students working in the universities close to this place and in Southern Germany, comprising Hesse and Saar. The drawback of these programs is a limited number of participating states.

Catalytic courses taught at universities in Italy are divided into three groups depending on students' curricula, which can be aimed at educating chemists, chemical engineers or industrial chemists.

The courses for chemists are based on «classes of catalytic reactions» (catalysis for the environment, H_2 production, homogeneous catalysis; hydrogenation; asymmetric catalysis, polymerization, etc.); on «fundamentals for activation of molecules» (catalyst requirements for activation of N_2, H_2, CO, NO; methane and hydrocarbons) and on «a classical organometallic approach» (metal complexes, ligands; homogeneous catalysis for hydrogenation, hydrocyanation, carbonylation, etc.; heterogeneous catalysis for ammonia synthesis, etc.).

Courses based on «principles + industrial technologies» are given for industrial chemists at BSc level and include, besides covering fundamentals, also several industrial catalytic technologies, such as for example production of terephthalic and acetic acid, acetaldehyde, etc. Courses based on the concept «Catalysis for society» also aiming at future industrial chemists include such topics as catalysis for pollutants abatement, methanol and hydrogen economy, etc. In some universities courses devoted to chemistry of catalysis at MSc level are given comprising fundamentals of catalysis, characterization, adsorption, catalytic kinetics, analytic techniques, laboratory reactors and examples of catalytic processes described through concepts of sustainable chemistry (process efficiency, integrated technologies, atom economy, environmental compatibility, etc.).

There are also classical catalysis courses based on «an engineering approach», which include besides industrial preparation of catalysts, also characterization, kinetics and mass transfer, reactors and industrial examples.

A highly segmented approach in education of catalysis is typical for USA with no standard coursework used or a standard text covering catalysis taught. For students specializing in chemistry the primary focus is on molecular catalysis thus catalysis courses mainly cover physical chemistry of catalysis from reaction kinetics perspective (steady-state approximation, Michaelis-Menten kinetics, etc.) with a very limited treatment of heterogeneous kinetics and catalysis. Chemical engineering curricula include besides physical chemistry principles of kinetics also chemical reaction engineering and heterogeneous catalysis *per se*, which is practiced in US mainly by chemical engineers.

While in Europe, i.e. above mentioned Germany or the Netherlands, which will be discussed below, some countries have an organized catalysis training courses for PhD students, there is no such program in the US with individual universities offering short courses mainly for professionals from industry.

It is interesting to note that some unique aspects of graduate education in USA are apparently not known for many European researchers and prospective students.

Many of those who attended the above mentioned symposium learned with surprise that individual research groups and professors from (all) top US chemical engineering and chemistry departments cannot directly recruit graduate students. Instead students apply to the university and are assigned to a PhD advisor and a particular group after arriving on campus, thus a PhD position in a specific group cannot be guaranteed.

Hiring of postdocs is done in a very different from PhD students' process as they are hired directly by the research group, and not by the department.

An interesting example of teaching various catalysis courses comes from Novosibirsk State University, where in the last five years 85 MSc have graduated from the Chair of Catalysis, which is very closely connected to Boreskov Institute of Catalysis. A peculiarity of the education system in Novosibirsk is that during the first three years general chemistry courses are given at the university, while the last two years of specialization are spent at so–called graduating chairs placed in various institutes of the Russian Academy of Sciences located in the same city.

Lectures are given by scientists working at these academic institutions and it is thus not surprising that out of 85 graduates 66 were admitted to the PhD program at Boreskov Institute. During their fourth and fifth years at the university all MSc students have to take 13 courses on various aspects of catalysis including separate courses on adsorption and porous structure; analytic methods in catalysis; chemical engineering; fundamentals of catalysis; catalysis and sustainable development; quantum chemical methods in catalysis; kinetics of heterogeneous catalytic reactions; magnetic radio spectroscopy; molecular design of catalysts; scientific basis of catalyst preparation; optical spectroscopy; X-ray methods in catalysis; modern approaches and techniques for catalytic measurements; thermodynamics of working catalysts. The diploma work (or MSc thesis) in fact is an extensive research project, which lasts almost two years.

Similar to Novosibirsk many courses on catalysis are offered in Lomonosov Moscow State University (MSU), including those on mechanisms of catalytic reactions; scientific basis of catalyst preparation; physical methods in heterogeneous catalysis; nanocatalysis, synthesis of zeolitic catalysts. Large and multidisciplinary trained scientific staff (in addition to staff focused primarily on teaching) is a specific feature of the Chemistry department of this University, providing each student, including those specializing in catalysis, a possibility to perform experimental or theoretical research under the guidance of an experienced researcher using modern scientific equipment (purchased by MSU Program of Development) during preparation of course and diploma works. Another peculiarity of education at MSU is an integrated 6-year education with so called diploma of a specialist after graduation. This approach differs from other Russian universities working according to the Bologna system (BSc and MSc stages). BSc graduated from other Russian or foreign universities can take MSc course as the last two years of the 6-year curricula.

Other Russian classical universities also educate chemists with the major in catalysis having similar courses. In departments of chemical technology and chemical engineering in the same country courses on a more applied side of catalysis are given. An example is Department of General Chemical Technology, Kazan University of Technology offering courses in fundamentals of catalysis in chemical technology, and in theoretical foundations of catalytic processes. The theoretical part includes the main features of homogeneous and heterogeneous catalysis. Substantial amount of time is devoted to provide the students with the first-hand experience. Besides doing laboratory works in the own university the students have a rare possibility to do labs in the research center of a large petrochemical complex Nizhnekamskneftekhim, located some 200 km away.

In Russian universities lecturers in catalysis, as in other fields of chemistry, have limited possibilities of ad hoc course changes because the main content of each lecture or lab course needs to be approved by the chair staff. However, examples and topics from the recent literature can be easily added by lecturers to the backbone of the course approved by administration. Apparently such a broad range of rather rigid courses offered at individual Russian universities cannot be given in other places at

least in Europe, where the focus is on a lower number of more flexible courses. This is understandable as education in Russia and maybe in few other places in the world retains many features of the old Soviet system with mass production of scientists and engineers, thus requiring very early and too detailed specialization. Selection of the major in many places is done prior to entering a particular university by students who just turn 17!

Contrary to this approach much more broad education is a feature of at least European universities where the students might find jobs in various places not directly related to their major. Thus the emphasis on specialized education is shifted to the later stages of training (i.e. PhD schools).

An interesting case study is education in catalysis in Australia where the graduates majoring in catalysis cannot find jobs in industry and have to move abroad. Eight major Australian universities consume 85% of universities research budget and provide education to 70% of students. Chemistry and chemical engineering has a share of ca. 8% in the overall budget. In all major universities catalysis is covered as for example in University of Queensland, where catalysis is taught either as a part of an undergraduate chemical engineering course or is integrated in a course on principles and applications of materials for a sustainable society.

Contrary to undergraduate programs PhD programs in Australia do not require any formal courses, therefore no courses related to catalysis are offered at the advanced level. To somewhat compensate a lack of advanced education a course on catalysis for renewable energy conversion is offered for industrialists.

3. What to Improve?

In order to explore in a quantitative way how education in catalysis is done in Italy an experiment was done by Prof. Cavani, who interviewed 113 PhD students and post-docs working in the field of catalysis in various Italian universities. The questionnaire is shown in Figure 1.

1. Which is the catalysis-related area you are (or have been) more involved in during your PhD-Postdoc ? (more than 1 answer allowed)
Reactivity: homogeneous catalysis
Reactivity: heterogeneous catalysis
Synthesis of catalysts
Characterization of catalysts
Theoretical aspects of catalysis
Others (please specify) _____

2. Did you ever attend any specific course on catalysis ?
Yes
How many hours of lesson in the classroom ? ___How many hours of practical experience in the lab ?_____
No

3. If you answered Yes in question 2: **You attended the course during:**
Your Bachelor degree
Your Master degree
Your PhD

4. If you answered Yes in question 2: **How was the course you attended organized ?**
It was more based on theoretical aspects of catalysis
It was more based on industrial aspects of catalysis
It was more based on the applicative aspects of catalysis (for example, classes of catalysts for oxidation, for hydrogenation, for decontamination….)
It covered all aspects of catalysis in an equal manner

5. If you answered Yes in question 2: **Do you think that the course you attended should have been delivered in a different manner ?**
No, it was well done
Yes, it should have been more based on practical aspects
Yes, it should have been more based on theoretical aspects and fundamentals
Yes, it should have included also practical experience in the lab

6. If you answered Yes in question 2: **During the course on catalysis you attended, did the teacher ever show you a catalyst in its industrial shape ?**
No
Yes

7. During your academic studies (Bachelor degree, Master degree and PhD) have you ever visited an industrial chemical plant ?
No
Yes, it was a catalytic process
Yes, but it was not a catalytic process

8. What is your general opinion on "catalysis" ? (more than 1 answer allowed)
It is a discipline with a solid theoretical background, which allows to provide a clear interpretation of experimental results obtained in catalytic experiments
The catalytic behavior of catalysts can be predicted at a certain extent
It is a discipline with a weak theoretical background, and mostly based on empiricism
The catalytic behavior of catalysts is unpredictable
It may truly contribute to the growth of the wellness of society
It has little effect on the improvement of society needs and on development of societal challenges

Figure 1. Questionnaire prepared by Prof. F. Cavani (University of Bologna)

Even if the courses are supposed to be very practically oriented (Figure 2) interestingly enough almost 50% of respondents spent very little time in the lab (Figure 3) during courses attended in Bachelor or Master Degrees.

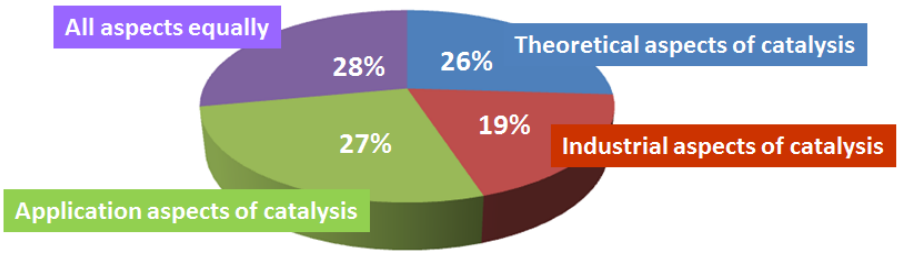

Figure 2. Respond of Italian PhD students and postdocs to the question on what was the focus of the catalytic course they have taken. Courtesy Prof. F. Cavani

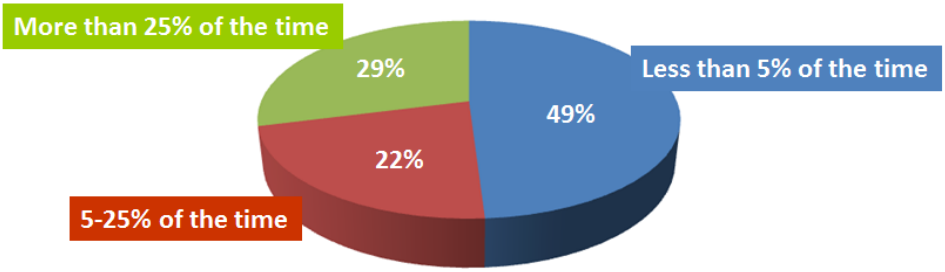

Figure 3. Respond of Italian PhD students and postdocs to the question on how much time was dedicated to laboratory practice. Courtesy Prof. F. Cavani

Not surprisingly 27% feel that more experimental work should be done and another 20% would like that more practical aspects should be addressed.

During academic studies at all levels (Figure 4) from BSc to PhD 40% have never visited an industrial chemical plant, and among those who visited, approximately one third got an industrial exposure on chemical processes not dealing with catalysis.

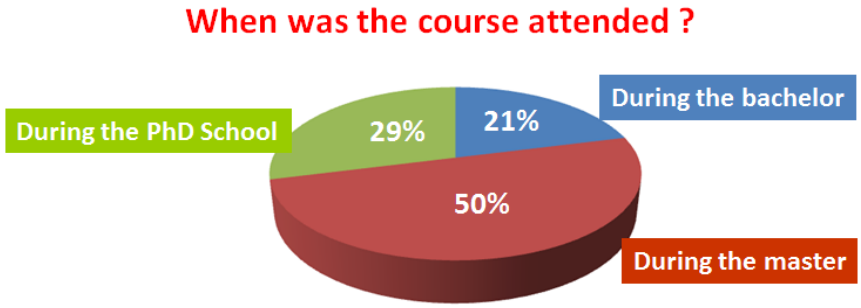

Figure 4. Respond of Italian PhD students and postdocs to the question on when was the course attended. Courtesy Prof. F. Cavani

While 90% of respondents appreciate importance of catalysis for society at large, a non-negligible number (12%) considers catalysis a discipline with a weak theoretical background, mostly based on empirical approaches and assumes that behavior of catalysts is almost or fully unpredictable.

To ignite the interest of students and relate catalysis to the current problems of the society and thus the everyday life of students more and more embraced with environmental consciousness in some catalytic courses green chemistry aspects of catalysis are specifically emphasized. This can be related to application of catalysis for biomass valorization, energy generation, synthesis of new materials, sustainable development, remediation of pollution, etc.

As an example courses in Chalmers (Gothenburg, Sweden), besides covering the basis of catalysis, pay a special attention to catalytic emission control which is the key research area of this university.

4. A Bit on Methodology

A nonconventional flipping approach to teaching of catalysis related courses is practiced in Eindhoven University of Technology (The Netherlands). Flipping means that what traditionally has been done inside classroom is done outside. Namely the students view online lectures and the time in classroom is used for learning-based activities, i.e. repeating main points, deepening knowledge, solving exercises, etc. In the Netherlands in general the BSc level chemical engineering and chemistry profiles do not contain explicit catalysis courses, as it is incorporated in inorganic chemistry, reaction kinetics and chemical reaction engineering courses. The MSc program with chemical engineering specialization contains a mandatory course “Catalysis: Science and Technology”, covering heterogeneous catalysis (75%) as well as homogeneous

and biocatalysis (25%). It is required from the students to write an essay on certain catalytic processes or reactions. This course became so popular that currently nearly all MSc students in the chemical engineering master and the chemistry master take it increasing participation number more than two fold (from 45 to 100+).

A more in-depth going course on modern concepts of catalysis, focusing on heterogeneous/homogeneous catalysis as molecular science, is elective. Chemistry specialization in the Master of Science program from the same university incorporated catalysis as a part of a mandatory course on advanced inorganic chemistry.

A special feature of the catalytic landscape in the Netherlands is the existence of the Netherlands Institute for Catalysis Research (NIOK) PhD program offering an Integrated Catalysis course with exam/certificate. This one week intensive course, organized on a remote island in the northern part of the country, brings together ca. 60+ participants from academia and industry. Lectures at this course being mandatory for most partners of NIOK are given by Dutch professors working in various fields of catalysis as well as by industry representatives.

Figure 5. Some textbooks covering various aspects of catalysis

The book ”Catalysis: an integrated approach” (Figure 5) based on this multidisciplinary course describes various industrially relevant reactions, which are catalyzed by heterogeneous and homogeneous catalysts. The latest edition was published already some time ago (1999) and the new one is expected to be available next year. Some other textbooks mentioned during the symposium on catalysis education are also shown in Figure 5.

A book aiming at BSc and MSc students should probably cover ideally physical chemistry of underlying concepts catalysis, catalyst preparation, characterization and testing, main chemical processes, combining atomistic description with chemical engineering approaches.

Apparently writing textbooks is a very time consuming exercise and in times when success of research groups is measured in papers published in top international journals, investing enormous amount of time in textbook writing requires dedication and a bit of altruism since financial incentives are almost non-existing.

In addition to the integrated course, specialized courses for PhD students are organized by NIOK every second year on the following topics: characterization in catalysis; advanced catalysis engineering; homogeneous catalysis. The course entitled “Catalytic Surface Science” is given every second year at the MSc level.

Although this graduate school seems to be rather successful, an apparent threat exists in the Netherlands because of a push from various universities towards local graduate schools rather than a national one.

5. Conclusions

It seems that because of multidisciplinary nature of catalysis requiring teaching it to (physical, organic, inorganic, industrial) chemists, chemical engineers and physicists there are no unified approaches to catalysis education. Moreover, there is a clear lack not only of coordination, but also of information flow between different countries, and sometimes between different universities located nearby.

Smaller groups not focusing on catalysis research and with fewer resources will certainly benefit from having an access to at least slides or other distribution materials prepared at top research institutions. Some sort of a depositary might be one of the options, which can be further explored.

Suggestions about improving teaching efficiency of at least applied catalysis are apparently clear as a more direct involvement of chemical industry is required with preferably students’ internships at the industry labs. The latter exposure to the real world has at the same time inevitable problems with for example secrecy, safety and availability of the trained personnel in industry to deal with students. Another option would be to ask retired scientists from industry to spend some time in university labs by advising students, helping in project preparation and analysis of results. Finally lectures teaching industrial catalysis might spend some time in industrial catalysis centra to get a better feeling about the industrial practice (catalyst synthesis, shaping, reactor loading, deactivation, regeneration, etc.)

Another suggestion is related to encouraging the exchange of the best education practices. While the journals devoted to chemical and chemical engineering education should certainly continue to publish papers devoted to some particular issues of education in catalysis, *Catalysis Science and Technology* journal can for example take an initiative to serve as a venue for general discussions on curricula and educational tools becoming thus a primary forum not only for top quality science, but also for catalysis education.

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Statement of Competing Interests

The authors have no competing interests.

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