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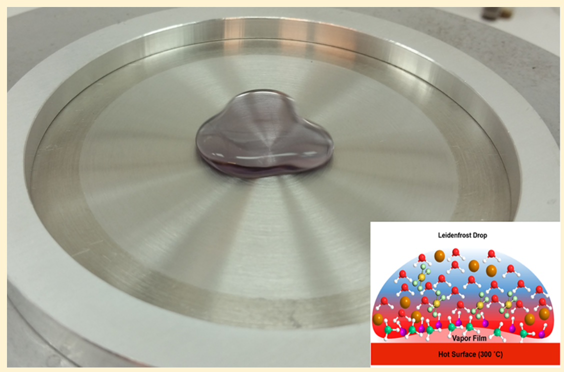
Innovative Education and Active Teaching with the Leidenfrost Nanochemistry

Mady Elbahri,*,[†] Ahmed Soliman,[†] Kirsi Yliniemi,[‡] Ramzy Abdelaziz,[†] Shahin Homaeigohar,[†] and Eman S. Zarie[†]

[†]Nanochemistry and Nanoengineering, Department of Chemistry and Materials Science, School of Chemical Engineering, Aalto University, Kemistintie 1, 00076 Aalto, Finland

[‡]Department of Chemistry and Materials Science, School of Chemical Engineering, Aalto University, Kemistintie 1, 00076 Aalto, Finland

Supporting Information



ABSTRACT: The best learning outcomes are rarely achieved without motivating the learner, and in this regard, active teaching and learning methods have been proven useful. Here, we introduce the "*learn and innovate*" strategy to enhance the students' interest, conceptual understanding, and deep learning under full guiding instructions. Moreover, by this strategy, we encourage the students to conduct an independent research while acquiring high-level thinking skills. Designing appropriate instructional strategies and innovative research tasks and media, which leads to collaborative/cooperative learning, enhances the students' interaction with the course materials. The method supports the students to gain self-confidence, motivation, and scientific skills to address different research challenges at early stages while enhancing their learning level. In this context, the adopted strategy fosters a first semester master student to deeply understand the new "Leidenfrost Nanochemistry" phenomenon to synthesize Au nanoparticles. Acquiring such knowledge, the student can participate in solving an exploratory research problem and the related experimental challenges. The "learn and innovate" approach has been proven to be a pivotal and novel active teaching strategy to stimulate the active learning of students and the innovative education-based *Aha!* effect.

KEYWORDS: *Graduate Education/Research, Collaborative/Cooperative Learning, Aqueous Solution Chemistry, Green Chemistry, Learning Theories, Nanotechnology, Student-Centered Learning*

■ INTRODUCTION

Despite the popularity of learning theories,[1,2] there is still a lack of the research-based learning approaches giving rise to in-depth understanding and advanced academic and research skills.[3] Introducing the students to exploratory active learning environments can increase their early research interests while enhancing their deep learning motivation. In this context, exploratory research provides appropriate learning environments (i.e., alignment) while the teachers instruct and advise the students to shape their learning and research activities to reach the outcome.[4] Here, the main challenge is the careful design of the learning environment. Therefore, the question is "what to do" to enhance the learning process, to motivate the students and to acquire the planned learning outcomes. With regard to uncovering "what works", we believe that getting the full attention and active participation of students necessitates the development of exciting tasks along with the active teaching strategies, promoting the learning process.

To prove the efficiency of the concept of "learn and innovate", here, we have designed an exploratory research-based learning strategy whereby 12 master students collaboratively/cooperatively learned the principles of synthesizing gold nanoparticles in a controlled manner via the Leidenfrost nanochemistry phenomenon.

The synthesis of Au nanoparticles and nanocrystals has been extensively studied since Michael Faraday's seminal work.[5] Among all the methods developed, the so-called Turkevich method based on the citrate reduction of Au(III) ions in a solution[6] is considered to be a benchmark technique for Au nanoparticle (Au NP) synthesis. More precisely, the Turkevich method deals with the sodium citrate ($Na_3C_6H_5O_7$) reduction of a gold precursor ($HAuCl_4$). The method has been introduced as an educational means for introducing the nanoparticle synthesis and/or for exploring color tunability in nanoscale in several teaching and pedagogical training and experimental laboratory courses.[7−10] However, controlling the

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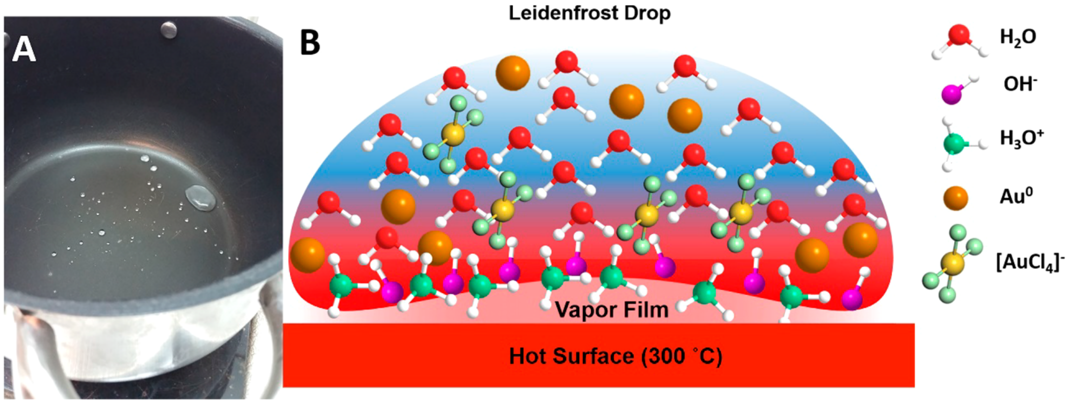

Figure 1. Water drops bounce in a kitchen pan (A). Schematic illustration of the chemistry taking place inside the Leidenfrost drop (B).

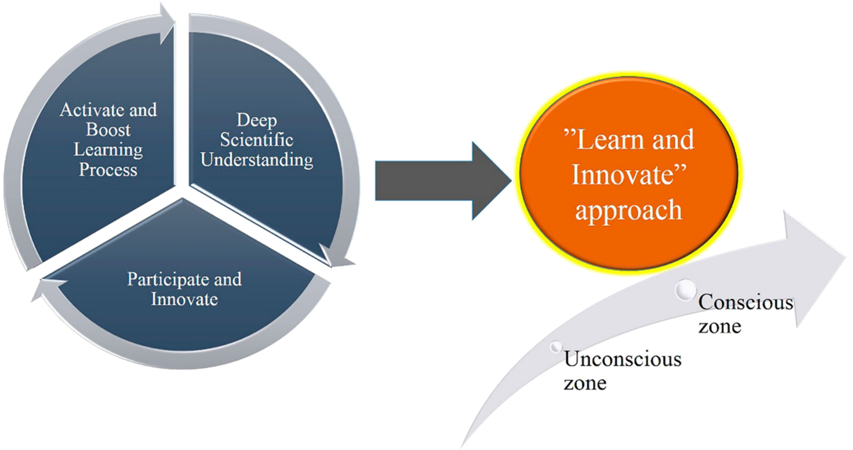

Figure 2. Core philosophy of the "learn and innovate" approach.

nucleation and growth of the nearly monodisperse gold nanostructures is a key challenge at both fundamental and technical levels.[11] Despite simplicity and eco-friendliness of the Turkevich method, the synthesized nanoparticles suffer from polydispersity, i.e., a heterogeneous size distribution and irregular shapes, stemming from the overlap of nucleation and growth steps.[12]

As an advanced alternative nanofabrication method, the Leidenfrost chemistry is a reducing agent-free route for the synthesis of nanoparticles such as Au NPs.[13] In our recent work, we emphasized the superiority of the Leidenfrost technique over conventional chemical methods in controlling the particle size distribution through physically separating the nucleation and growth phases.[14] Inspired by such an important finding, here in our study, the exploratory research question was whether applying the Turkevich parameters (i.e., adding citrate/adjusting pH, etc.) inside the levitated Leidenfrost drop enables control of the particle size distribution. An exploratory research team composed of several first semester master students advised by some teachers/instructors researched this topic.

■ BASICS OF THE LEIDENFROST CHEMISTRY

The dance of a water drop on a hot frying pan is an everyday event that we see in kitchen. This physical phenomenon, first investigated and documented by Leidenfrost and thus named after him, can be described as a process in which a liquid drop levitates above a hot solid surface due to presence of an insulating vapor film, created at the solid−liquid interface, Figure 1A.

Despite the simplicity of the bouncing behavior of a water drop on a hot surface at first look, it seems to be a totally mysterious effect. Since the first explanation of the phenomenon by Leidenfrost, levitation of a water drop on its own vapor film has been solely tackled from a physical point of view. In contrast, as a breakthrough, we discovered a unique chemistry progressing inside the levitated water drop, called "the Leidenfrost chemistry".[13,15] In our previous studies, we proved the existence of an overheated zone composed of a vapor/superheated liquid underneath the drop (i.e., the levitation zone) and a temperature gradient in the Leidenfrost droplet. Self-ionization of water molecules occurs in the overheated zone, thus leading to a local increase in the hydroxide (OH^-) ion concentration. This basic condition is resulted from the removal, i.e., transfer, of hydronium ions (H_3O^+) to the vapor film, Figure 1B, even though the overheated zone is assumed to be a quasiclosed medium.

Such conditions are favorable for green nanofabrication in the levitated Leidenfrost reactor. The mechanism of the nanoparticle formation inside the Leidenfrost drop resembles the dynamic underwater chemistry taking place near the volcano gates deep in the oceans.[14] The hydrodynamic characteristics of water under the Leidenfrost condition are transformed so that its involvement in the reactions ongoing in the drop is allowed much more than in an ordinary solvent. The fast evaporation and phase expansion occurring upon the

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touch of the water drop on a preheated substrate lead to induction of charges across the hot interface, as shown earlier.[13,14] The fast evaporation of the water drop causes the local increase of the precursor (salt) concentration and of the pH in the surrounding medium. Increasing the local pH facilitates the formation of a variety of nanomaterials of metal, metal oxide, and hydroxide in a medium wherein the role of OH^- might be either as a catalyst or as a redox mediator. With respect to the synthesis of Au nanoparticles, depending on the OH^- and citrate contribution (the Leidenfrost and Turkevich method, respectively), the reduction reactions can occur according to the proposed following equations:

The citrate-free reaction (when OH^- acts as the reducing agent):[16]

$$12OH^- + 4AuCl_4^- \rightarrow 3O_2 + 16Cl^- + 4Au^0 + 6H_2O$$

The citrate-free reaction (when OH^- acts as a catalyst facilitating the discharge reaction):

$$4OH^- + 2AuCl_4^- \rightarrow O_2 + 2H_2O + 2Au^0 + Cl_2 + 6Cl^-$$

The citrate-based reaction (at 100 °C):[17]

$$2AuCl_4^- + 2H_2O + C_6H_5O_7^{3-} \rightarrow 2Au^0 + 3H^+ + 8Cl^- + 3CH_2O + 3CO_2$$

PEDAGOGICAL RESEARCH DESIGN

The main goal of the "learn and innovate" approach, as shown in Figure 2, is to guide a student from the unconscious zone to the conscious zone in fundamental science and research on an explicate subject (e.g., the Leidenfrost nanochemistry). The core concept of the approach can be considered as an active education style that can activate and boost the students' learning processes while deepening their scientific understanding of an innovative phenomenon. The process is aimed at teaching students more about the thought process behind the experimental research, at guiding them in finding a solution for the challenges emerging in the research environment, and at developing innovative and out of box thinking skills. To fulfill such objectives, students work in small groups to enhance their collaborative and cooperative learning processes.

The "learn and innovate" approach designed by the leading author is based on two concepts of innovative education and active teaching. Innovative education aims to teach the students at an early stage new and innovative concepts that are beyond the state of the art in research and not found in the textbooks. It is more than teaching a technology; rather, it addresses the training of a new generation of students, who are scientifically updated, motivated, and willing to acquire deep knowledge and scientific skills. Toward this goal, a series of educational activities, mentorship, and class action were formulated and designed by the responsible teacher. Such a broad range of rational tasks can develop the mental and technical skills assuring the learning and comprehension of various concepts thus active teaching.

The pedagogical learning aims of the "learn and innovate" strategy include the following:

- to introduce the student to a new and unknown scientific territory;
- to stimulate and to enhance in-depth learning;
- to conduct an exploratory research at early stage;
- to develop the skills related to out of box and critical thinking;
- to develop collaborative and cooperative learning/researching skills;
- to develop and to enhance reading and writing skills;
- to develop the ability of formulation of scientific questions and hypotheses and to identify new clues;
- to participate in the planning of own experimental steps; and
- to identify, to evaluate, and to support early stage excellency.

In our study, the Leidenfrost chemistry was the central curriculum and was selected as an exploratory research for production of the pedagogical insights while formulating the scientific questions. In this exploratory research, the following objectives were sought:

(1) Familiarity with the basic details, settings, and concerns. Fundamental understanding of the Leidenfrost phenomenon and the nanochemistry occurring in a levitated Leidenfrost drop.
(2) Generation of new ideas and assumptions. Finding the conditions necessary for the controlled synthesis of nanoparticles inside the Leidenfrost drop.
(3) Development of experimental recipe tentative theories or hypotheses: How are nanoparticles formed inside the drop?

TEACHING METHODS AND LEARNING OUTCOMES

The Leidenfrost chemistry experiment was conducted in several manners with particular teaching methods, as summarized in Figure 3. Starting with the direct instruction as passive and low-teaching learning given by the teacher, the students learned about the Leidenfrost phenomenon and its execution leading to the synthesis of nanoparticles. Learning by seeing was carried out through the "Lab in Classroom", which

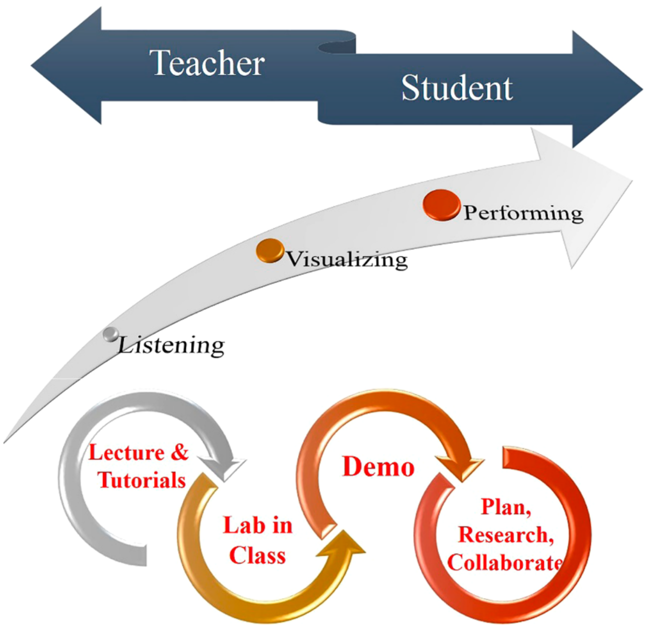

Figure 3. Different teaching manners utilized in the activity and their interrelation.

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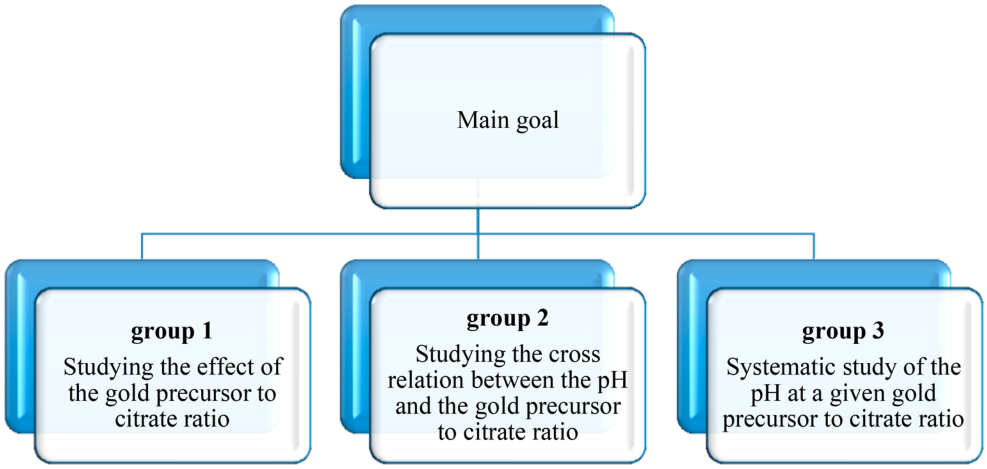

Figure 4. Research questions assigned to each group of the students.

was introduced and performed by the nanochemistry group. We offered prerecorded experimental videos (Supporting Information Video 1) regarding the phenomenon and the chemical reactions occurring in the levitated drop. The session was accompanied by the teacher's explanations and discussions to enhance the students' in-depth conceptual understanding. As already proven, the method is able to raise the students' interest and to increase their interaction with the teacher. Furthermore, it encourages the students to formulate several questions and to imagine various experimental designs. Thus, the method is considered as a high-teaching method given by the teacher. This step was followed by experimental demonstrations and discussions in the lab by the instructors. In this regard, further questions were formulated and answered by the students and instructors, respectively. In this session, the students became aware of the available resources, i.e., laboratory space, chemicals, and relevant instrumentation. It is worth noting that, prior to this course, the students had passed a separate laboratory course during which they learned the basics of selected characterization methods such as scanning electron microscopy (SEM), ultraviolet−visible spectroscopy (UV−vis), and dynamic light scattering (DLS). Afterward, the teacher challenged the students by assigning a high-level research task. The task studied by the students was exploratory research to find the parameter(s) enabling the fabrication of monodisperse nanoparticles under the experimental condition. In this regard, the effect of pH and citrate ions concentration on the size of the synthesized gold nanoparticles and thus the emerged color in the levitated drop was studied.

As seen in Figure 4, the students were divided into small groups so that each one worked collaboratively on certain parameters and all of them worked synergistically to find out the clue. This mechanism was aimed to govern a connection between the students and to allow them to actively participate in solving their tasks via a collaborative way of thinking by talking and discussing with each other.

Having introduced the exploratory research to the students, the teaching method proceeded to the high-tech centered learning, "Research-Based Learning". It started with a "reading circle" whereby the students familiarized themselves with the scientific literature related to the topic; 2−3 papers including refs 13 and 15 were provided as a starting material. The students were asked to find further information and sources that help them solve the given scientific problems. Later on, they were asked to design a research plan. On the basis of all the information given to them, each group had to write a research plan, "writing circle", that included a short introduction about the research problem, materials and methods, timetable, and safety considerations.

Upon the teachers accepting the research plan, the students performed the research quasi-independently in their own groups (4−6 h laboratory sessions everyday for 3 weeks): during these sessions, the teachers were always present in the laboratory for safety reasons and answered the students' likely questions. However, the students were expected to follow their own research plan. Also, there was a weekly tutoring session where each group could discuss with the teacher about the research plan for the next week and possible modifications, the encountered problems, and their solutions in more detail. In addition, a daily short tutorial with each group was planned not only to discuss with the students their results and faced difficulties but also to help improve their technical skills during the experiments. The reason for considering such tutorials is the uniqueness of teaching/research situations with respect to the scientific levels, skills, and learning styles of the students. A classroom action was performed by the advisor teacher, "responsible professor", through several lab visits and office meetings with each group to ensure the progress in the learning aims and outcomes. The key points in this activity were the debriefing and evolution of the "learn and innovate" strategy in terms of feedback on the students' progress and their reflection, following up their collaborative and cooperative activities, motivating them and enhancing the students' self-confidence, as well as impressing upon them how important their research is. An example for the motivating approaches was informing the students that the research they were carrying out would be published and they would be regarded as coauthors depending on the level of their contribution to experimental and results and discussion sections. This step was believed to have a remarkable impact on their motivation and research activity, as all of them were interested in being coauthors of a publication for the first time. However, later, on the basis of the journal policies and agreement with the students, their names were transferred to the Acknowledgments.

As the next step in the "innovate and learn" approach, the modified Bloom's taxonomy by Anderson and Krathwohl[18] was used in formulating the intended learning outcomes

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Table 1. Concentration, Volume, and pH of the Reaction Precursors

sample	$HAuCl_4$ (mM)	$HAuCl_4$ (mL)	sodium citrate (mM)	added sodium citrate (mL)	added 0.5 M NaOH (μL)	pH
A	0.5	4	10	0.5	N/A	7
B	0.5	4	20	0.5	N/A	6.5
C	0.5	4	100	0.5	N/A	6.5
D[a]	0.5	4	10	0.5	10	8.5
E[a]	0.5	4	10	0.5	10	8.5

[a]Note that D is synthesized via the Leidenfrost method, while E is synthesized via the Turkevich one.

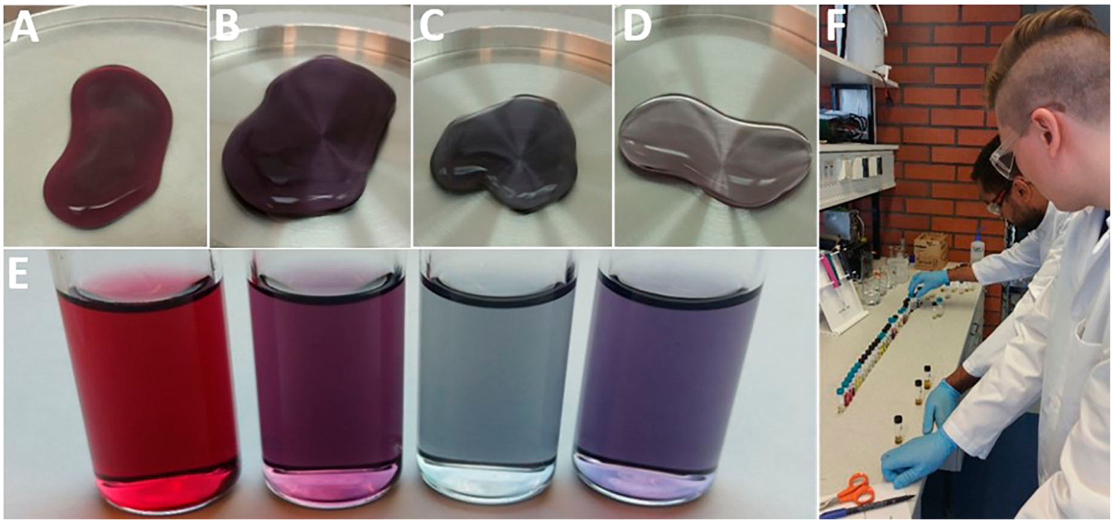

Figure 5. Different Au-NP-based plasmonic colors emerged in the Leidenfrost levitated drop (A−D, corresponding to the samples labeled in Table 1). The up-scaled production of the controlled sized Au NPs (E). Students participate in the exploratory research in accordance with the activity plan (F).

(ILOs). Anderson and Krathwohl state that in the cognitive domain there should be another level (create) after the evaluation level.

After the research-based-learning course, the students could (the intended learning outcomes):

- Explain the Leidenfrost phenomenon and the involved chemistry;
- Develop an experimental recipe to synthesize nanoparticles by establishing the Leidenfrost conditions;
- Correlate the controlled nucleation and growth stages to the size distribution of the nanoparticles;
- Identify the effect of pH and Au/citrate ratio on the nanoparticles' size;
- Carry out a complete experimental investigation including design, equipment building, data acquisition, and analysis;
- Present/report the scientific results in a logical manner.

■ MATERIALS AND METHODS

All the stock solutions were freshly prepared prior to the experiment by the instructors using analytical grade chemicals and deionized (DI) water. The prepared stocks were 0.5 mM gold(III) chloride trihydrate ($HAuCl_4$) and 100 mM trisodium citrate ($Na_3C_6H_5O_7$). The students then diluted the stock solutions and adjusted the pH according to Table 1. The freshly prepared precursor reagent was dropped on a preheated aluminum plate with a temperature of 300 °C, and once the color was stabilized as dark red/black (recognized visually), the colloidal Au NPs were collected and cooled down in an ice bath promptly to finish the growth stage of the nanoparticles.

The polydispersity index (PDI) of the prepared Au NPs, i.e., the measure of the breadth of their size distribution (the more monodisperse the nanoparticles, the smaller PDI), was characterized via dynamic light scattering (Malvern zetasizer-nano ZS) while the plasmon resonance peak was determined by a UV−vis spectrophotometer (Varian Cary). The specific wavelength of the plasmon resonance peak can be correlated to the Au NP size and agglomeration state.[19] In general, the smaller the particle is, the broader the peak will be. Moreover, agglomeration of nanoparticles will eliminate the peak.

■ SAFETY CONSIDERATIONS

During the synthesis, all the students had to wear the personal protective equipment (PPE). Furthermore, the students had to avoid heat hazards, e.g., the very high temperatures of hot plates (e.g., up to 300 °C). Despite the small volume of the reaction mixture, the synthesis had to be performed under a fume hood. All the chemical wastes had to be disposed into the designated and labeled waste bottles.

It is worth noting that safety considerations were also a compulsory part of a written research plan. This means that the students had to find the material safety data sheets for all the chemicals and the list of the possible hazards of all the chemicals. Also, they had to plan the waste collection and think about the typical risks existing in different subtasks of the work package.

■ RESULTS AND DISCUSSION

As soon as the premixed Au precursor solution containing drop touches the preheated aluminum plate, it levitates on the

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formed vapor layer, as seen in Figure 5A–D. The levitation takes place due to instantaneous vaporization of the solution touching the hot plate, leading to the Leidenfrost state.[13,15,20] The charge chemistry is induced by the temperature gradient of the levitated drop and self-ionization at the hot interface. Meanwhile, the color starts to change, indicating the beginning of the Au(III) discharge reaction. The various postulates of the reduction and synthesis mechanisms were mentioned earlier in the section "Basics of the Leidenfrost Chemistry".

This method results in the synthesis of the Au nanoparticles whose size is controllable by adjusting the citrate/Au(III) ratio and pH, as deduced from the different colors of the colloidal Au NP containing solutions in Figure 5E, made by the students who conducted the research, Figure 5F. The determined PDIs of the synthesized particles imply their nearly monodisperse size distribution, as shown in Table 2. The recorded PDIs decrease significantly from the conventional Turkevich method under the normal boiling condition, sample E, to the Leidenfrost condition, sample D, using the same reaction mixture (Supporting Information Figure 1 shows the dynamic light scattering (DLS) graph related to sample D versus E). The high monodispersity of the synthesized Au nanoparticles (the Turkevich method under the Leidenfrost condition) can be attributed to the physical separation between the nucleation and growth steps[14] and (or) the seed mediation.[10] The latter is a consequence of charge separation in the colloid due to the existing thermal gradient in the Leidenfrost state and the activated hydroxide ions generated by the drift in the water self-ionization.[13]

Table 2. Average Particle Size (Hydrodynamic Radius) and Polydispersity Index of the Synthesized Au Nanoparticles, Measured via the DLS Technique

sample	A	B	C	D	E
average particle size (nm)	33	46	428	20	11
polydispersity index (PDI)	0.5	0.5	0.5	0.1	0.2

The localized surface plasmon resonance (LSPR) effect is collective oscillation of free electrons in plasmonic nanomaterials (e.g., Au NPs), caused by incidence of light.[21] The specific wavelength of the plasmon resonance peak can be correlated to the Au NP size and agglomeration. The LSPR peak of Au nanoparticles appears typically at 500–550 nm and can be easily traced by UV–vis spectroscopy,[22] as shown in Figure 6.

Samples A, B, and D show well-defined absorption bands that are notably red-shifted (i.e., increase in λ_{max}) with the increase of the particle size. In contrast, sample C shows no obvious absorption band, that is mainly attributed to the large size of the particles, i.e., agglomerates of finer particles. In fact, sample C containing microsized particles rather than nanoparticles offers no LSPR, as predicted by the Mie theory.[23,24]

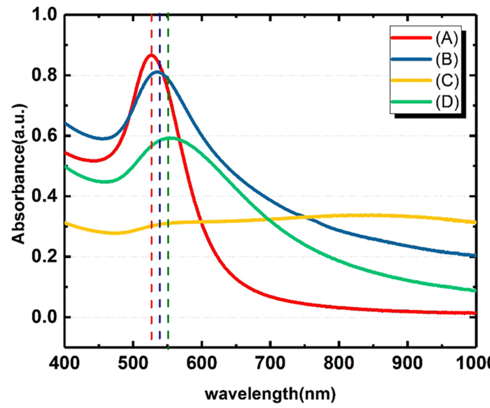

Figure 6. UV–vis spectra show the size dependent optical characteristics of the plasmonic Au nanoparticles (A–D correspond to the samples labeled in Table 1).

■ EVALUATION OF THE LEARNING OUTCOMES

On the basis of the classroom action and the instructors' report on the individual and group performance in the laboratory as well as the weekly student feedback, it was possible to evaluate and to modify the activity, if necessary. Moreover, such a feedback enabled focusing on the students' needs at an early stage to help them reach the planned aim while identifying early students' excellency. The final evaluation was based on individual student reports.

Obtaining weekly student feedback was essential to learn about the students' experience, motivation, scientific development, learning activities, and opinions for further improvement. The "class of action" by the responsible professor that was carried out in the second week of the activity, where the students could reflect on and discuss about what they are doing and how their understanding is changing, resulted in an impressive development and success of the adopted strategy. In this regard, the students had to answer the following questions:

(1) How did you find the organization and the structure of the lab?
(2) Why were we doing each activity at the lab?
(3) Was the given instruction enough to support you with the necessary items for the activity?
(4) Was the research plan discussion sufficient to understand the aim of the research?
(5) Were the instructors helping you to achieve your aim?
(6) Did the work help you to be independent and motivate you sufficiently?
(7) What is the overall evaluation of the week?

The 12 students were asked to rate the quality criteria represented in the questions based on a Likert-type scale ranging from 1 to 5 at which 1 and 5 implied "needing improvement" and "excellent", respectively. The grade percentage was calculated by conversion of the average of the students' rates to percentage. As seen in Figure 7, the results show that all the students were able to fulfill both levels of learning outcomes, i.e., the aimed outcome of the "learn and innovate" strategy as well as the intended learning outcome of the project (the Leidenfrost chemistry).

Development of the students' learning skills within the frame of the active teaching approach is based on the activities designed by the responsible teacher. In this regard he considers the psychological (i.e., conscious and unconscious) and sociological (i.e., purposeful actions) aspects. Innovative education is a new and unknown territory for the students especially those at an early stage. In contrast to the traditional approaches where students have a prior knowledge and access to unlimited sources about the task, the innovative teaching approach is generic by lack of prior knowledge relevant to the study. Thus, it can induce uncertainty and even anxiety as the students are moving from the comfort and conscious zone wherein everything is relatively known (as seen in the conventional teaching methods) to the unconscious "un-

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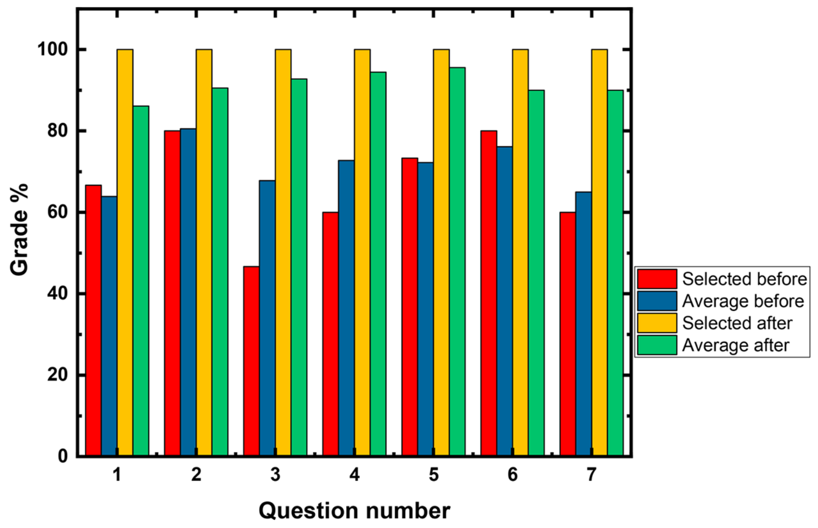

Figure 7. Selected (out of the three groups) and statistical average of the individual students' answers to the learning progress questionnaire (including the above-mentioned questions) before (red and blue columns, respectively) and after (orange and green columns, respectively) the "class of action".

known" zone in an unfamiliar environment. In this regard, in our study, avoiding detailed instructions, students were challenged with an explorative experimental research problem, "Preparation of the monodisperse Au nanoparticles by the Leidenfrost method", and asked to find (out) the best set of parameter(s) fulfilling the research objective. To realize the ILOs, the uncertainties and insufficient self-confidence of the students must be addressed. Furthermore, they should be encouraged to learn and perform new and innovative concepts, to find out a scientific pathway, to establish relationships between various subjects, and to acquire scientific skills needed for a successful research. Such an approach is clearly different from the students' earlier "conventional" laboratory experience and thus can be daunting when experienced for the first time. That was why all the students were struggling with their research tasks during the first week of the experimental work. This development was also seen in the weekly feedback questionnaire (Figure 7). The deep learning curve at the start (1st week) is not surprising as the students were exposed for the very first time to a new way of thinking with respect to their experimental work. This approach leading to the ILOs not only should lower the uncertainties and enhance self-confidence of the students but also help them increase their mental and scientific skills. For this reason, a collection of well-designed activities by the responsible professor including intensive supervision, guiding, class tutorial, and working in collaborative and cooperative manner along with the class action was adopted. Such tasks could raise the self-confidence, motivation, team work, and scientific skills and meet the preconditional rules of active research. Accordingly, the deep learning curve at the second week ascended dramatically, implying the successful execution of this type of learning and a new way of thinking by the students, as reflected in both statistical averages of the individual students' and selected answers to the learning progress questionnaire. The same positive feedback and similar narrative statements of the students, such as "A great Learning experience", "Mega good", "Very interesting work", "contributing to a real science", "people feel really exciting", "It is almost ideal but need more resources (time)", "Learn how to conduct a research and have experience in team work in laboratory condition", "I liked the discussion throughout the lab", and "Group research", imply the fruitfulness of the adopted approach. On the other hand, some students were satisfied with the scientific outcome of the approach and stated as "Leidenfrost phenomenon how to get critical pH", "Making interesting sample", and "learn new techniques".

From the teachers' point of view, this type of learning process is typical in the transformative learning theory, introduced by Mezirow,[25] where the change of so-called "frame of reference" is critical in order to achieve deep understanding of the topic. This process is sometimes also called "unlearning",[26] and for example, the weekly feedback questionnaire gives strong evidence that such a process takes place in this course when students are transforming themselves to active problem solvers in the laboratory environment. This transformation, which is in our opinion the biggest learning outcome of the introduced active teaching approach, was apparent to the professor/teacher leading the groups when a positive change in the mind-set of the students by intensive guiding was recorded. For instance, the motivation level, self-confidence, understanding of the scientific phenomenon, and operational skills clearly increased/improved during the second and third week.

It is noteworthy that the method mainly relied on active student participation under an intensive, planned, and designed guiding process from the teacher via "active teaching" and hence deviated largely from active learning, i.e., "constructivism",[27] where teaching and learning are based on the student and the teacher acts as a facilitator. In fact, the leading author's concept of constructivism resembles throwing the student in a pool to make him/her learn the swimming unless he/she has already strong and enough prior knowledge to construct atop of it. Among different educators/professors, there has always been a misinterpretation of "constructivism", which is a theory of how one learns and sees the world, with a prescription for how to teach as stated by Clark et al.[28] An extensive discussion of such perspectives and ideas is out of the scope of this article. Despite these controversies, we believe that active teaching which is a teacher-based approach with integrative active and cooperative activities appears to be a vital strategy to enhance the students' motivation, skills, deep

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learning, and thinking skills especially for the early stage students exposed to innovative and explorative education.

Upon completion of the research activities, the students were capable of writing a final report in a journal-article-like manner. The report was composed of introduction, experimental, and results sections, and was written in-group and finally accompanied by individual discussions and reflections. In the last part, the students had to justify the adoption of Leidenfrost chemistry as an emerging field, evaluate its usefulness, and scientifically criticize its limitations. In addition, they were encouraged to make their own scientific questions and to identify new clues. In this context, the reports have further reflected the understanding of the topic and the adaption of ILOs by the students.

■ CONCLUSION

There were 12 master students divided into 3 groups, and they conducted an exploratory activity. The general feedback by the students was positive. All the students understood the basic methodology of the work well and also learned about the Leidenfrost chemistry and exploratory research, though some students needed more hands-on teaching/experiments to fulfill the goals. The discussion with students and their weekly evaluation and feedback stressed the presence of an excellence-learning environment wherein they deeply understood what they were doing; this understanding was reflected in their motivation, self-confidence, and the *Aha!* effect, implying the success of our strategy. The most common comment of the students in their final report was about their deep understanding of the phenomenon and the simplicity of the Leidenfrost technique. Furthermore, they found the activity to be very fruitful and exciting, especially when their names are to be acknowledged in an article related to their exploratory research and learning skills development.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.7b00973.

DLS graphs implying the size distribution of the nanoparticles synthesized under the Leidenfrost and the Turkevich conditions (PDF, DOCX)

Experimental video showing the synthesis of gold nanoparticles via Leidenfrost reactor (ZIP)

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: mady.elbahri@aalto.fi.

ORCID

Mady Elbahri: 0000-0002-6720-1945

Kirsi Yliniemi: 0000-0003-2536-388X

Author Contributions

M.E. conceived the pedagogical concept and experimental idea, designed and followed up the pedagogical/experimental steps, supervised and mentored the instructors (A.S., R.A. and E.S.Z.), and mainly wrote the manuscript. A.S. contributed to the design and implementation of the laboratory experiments, presented the tutorial, and mentored the students in the laboratory. K.Y. contributed to the analysis and discussion related to the students learning process. R.A. contributed to the design and implementation of the Laboratory experiments and supervised the students in the laboratory. S.H. contributed to the design and implementation of the experiments, presented the tutorial, and mentored the students in the laboratory. E.S.Z. was involved in supervising the students during the characterizations and measurements. All the authors contributed to drafting of the manuscript.

Notes

The authors declare no competing financial interest.

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