CHALLENGES IN TEACHING ‘COLLOID AND SURFACE CHEMISTRY’

A Danish Experience

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Seven years ago we were asked, as one of our first teaching duties at the Technical University of Denmark (DTU), to teach a 5-ECTS-point course entitled Colloid and Surface Chemistry. The topic is both exciting and demanding, largely due to its multidisciplinary nature. Several “local” requirements posed additional challenges. The course is part of the international program of the university, typically at the start of the M.Sc. studies (7th-8th semester) and can be taken by students of different M.Sc. programs (advanced and applied chemistry, chemical engineering, or petroleum engineering). B.Sc. students toward the end of their studies can also take the course. Also, due to the multidisciplinary nature of the course topic, a wide variety of industries in Denmark has shown interest in the course, which has led to development of a separate industry course.

In this article we report on our experience from the first years of teaching the course and how teaching methods and course material have been adapted to meet the aforementioned challenges, as well as feedback and course evaluation from students. First, we present the learning objectives of the course followed by a discussion of the teaching methods used over the years. The most challenging topics covered in our course are highlighted as well as a discussion of the textbooks employed. Supplementary initiatives (*e.g.*, link to a laboratory course) are briefly presented followed by our assessment of the current status and some suggestions.

COURSE NATURE, CONTEXT, AND LEARNING OBJECTIVES

The time allocated for a typical 5-ECTS-point course at DTU is one four-hour block a week during a 13-week semester, followed by an examination. We have been during the last three years using the textbook of Pashley and Karaman[1] as part of the course material. Self notes from the teachers are

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also used; they are available to the students via the intranet system at DTU, called Campusnet. We have found it particularly difficult to find a suitable textbook that could fulfill the course requirements and be appealing to different audiences and the increasing number of students (Figure 1), and a discussion of the three textbooks used in the lifetime of this course is provided in Table 1. Further discussion on textbooks and teaching in Colloid and Surface Chemistry has been provided by Woods and Wasan.[11] The comments shown in Table 1 are based on the opinions of both the students and the teachers. We have, however, considered other textbooks as well,[4-10] but we have not found them suitable for our course.

The course is evaluated with a four-hour written "open book" exam (*i.e.*, all material available).

From the beginning of the academic year 2007-8, DTU adopted learning objectives as a standard part of all course descriptions in the course catalogue. The overall target of the course is to present to the students the most important principles and phenomena related to colloid systems and surface chemistry. These areas have important and extensive applications in the understanding and design of processes such as adhesion, lubrication, cleaning, enhanced oil recovery, and waste-water and air purification, as well in the understanding and design of products such as detergents, cosmetics, pharmaceuticals, polymer-containing items, and food. There are also numerous applications in nature, *e.g.*, fog, water droplets, and capillary phenomena.

The specific learning objectives of the course are for students to be able to:

- *Calculate surface and liquid-liquid interfacial tensions with various theories*
- *Use different theories for estimating the solid-liquid and solid-solid interfacial tensions and employ them in wetting and adhesion studies*
- *Recognize the various mechanisms of adhesion and use various methods (Zisman's plots, theories) for its assessment*
- *Describe the most important theories in surface chemistry*
- *Use the Gibbs equation for adsorption calculations*
- *Explain the creation of micelles (CMC) from surfactants and tell how CMC can be measured and how it depends on salt, temperature, and chain length*
- *Relate the adsorption in gas-solid and solid-liquid surfaces and use the Langmuir and BET theories for adsorption calculations*
- *Calculate the molecular weight and shape of colloidal particles*
- *Describe the most important (van der Waals and double-layer) forces between colloidal particles and their differences in relation to the intermolecular forces*
- *Explain the most important parameters in colloid force-theories (zeta potential, Debye thickness, Hamaker constant) and perform calculations with those*
- *Describe the DLVO theory for the stability of colloidal particles as well as compare the various mechanisms for steric stabilization*
- *Describe the stabilization mechanisms in emulsions (and foams) and design emulsions using various semi-empirical tools (HLB, Bancroft rule, etc.)*

These learning objectives, which are presented using active verbs, focus on the abilities or competencies the students must possess after they have completed the course.

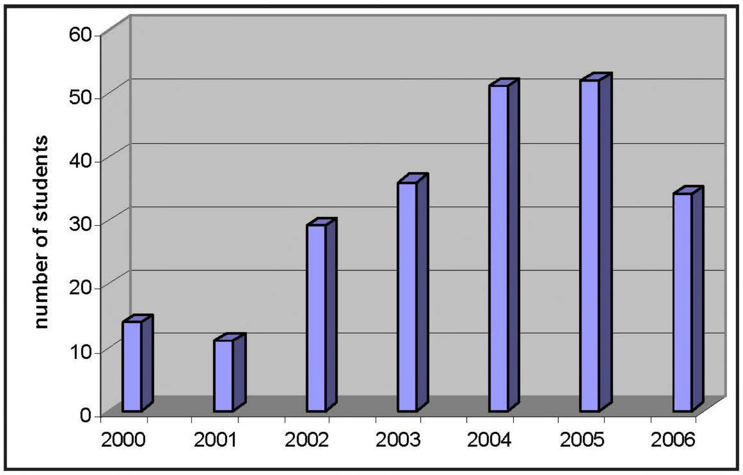

Figure 1. *Students in the course over the years.*

TABLE 1

Books on Colloid and Surface Chemistry Used in Our Course in the Period 2000–2006

Book	Used in period	Comments by students	Comments by teachers
Shaw[2]	2000–2003	Detailed presentations. Boring layout. No applications.	Extensive presentation of numerous topics. Includes exercises—not worked-out problems. No presentation of modern theories for interfacial tensions.
Goodwin[3]	2004	Too condensed. Too high-level.	Advanced textbook, requires previous knowledge of colloids and interfaces.
Pashley and Karaman[1]	2005–2006	Somewhat too brief, no details; easy to read, though.	Very interesting industrial case stories and worked-out laboratory exercises. Does not include chapter on colloid particles characterization.

CENTRAL TECHNICAL AND SCIENTIFIC TOPICS

Due to the multidisciplinary nature of the subject as well as the varying interests of the students, among other reasons, we have found it necessary from the start of the course to emphasize:

(i) *The applications of colloid and surface chemistry in various fields—especially chemical industry—including paints, adhesives and detergents, petroleum industry (especially the surface phenomena), materials with emphasis on polymers, cosmetics, agrochemicals, and food colloids (Figure 2)*

(ii) *The links between the most important topics and concepts as well as their interrelations*

One of the positive features of the currently used textbook[1] is the large number of "industrial stories" presented. The book, however, includes numerous applications "hidden" throughout the text and we felt it necessary to summarize those applications for the students.

We have found that presentations of key concepts and tools are extremely helpful in promoting understanding of the coursework as well as in assisting in practical applications. Equally useful is a summary of the key equations, considering the variety of topics covered.

The key concepts of broad importance covered in the course are:

1. *The estimation methods for surface and interfacial tensions, especially theories for the latter based on intermolecular forces and their applications to wetting and adhesion*
2. *Distinguishing between "general" laws and concepts and theories-specific equations, but also a demonstration of the major applications of the general laws especially of surface chemistry*
3. *The equivalency interrelation of the Gibbs adsorption equation with the adsorption theories and two-dimensional equation of state (surface pressure-area plots)*
4. *The structure-property relationships in surfactants and the complexity of the various factors affecting micellization and the value at CMC*
5. *The similarities/differences (both in terms of physics and equations) of the adsorptions at various interfaces: gas-liquid, liquid-liquid, liquid-solid, solid-gas, and how information from one type of interface, e.g., solid-gas, can be used in analyzing data in liquid-solid/liquid interfaces*
6. *The complexity of adsorption on solids—differences between gas, surfactant, and polymers*
7. *The complexity of solid surfaces and cautiousness needed in the interpretation of wetting-adhesion phenomena*
8. *How a variety of properties/measurements for colloidal particles (kinetic, optical, rheological) can yield important information for the particles—especially their molecular weight and shape*
9. *The similarities but also important differences between intermolecular and interparticle/surface forces*
10. *The essential concepts of the electrical and van der Waals forces between colloid particles—especially zeta potential, double-layer thickness, and Hamaker constants*
11. *The DLVO theory for colloidal stability, how*

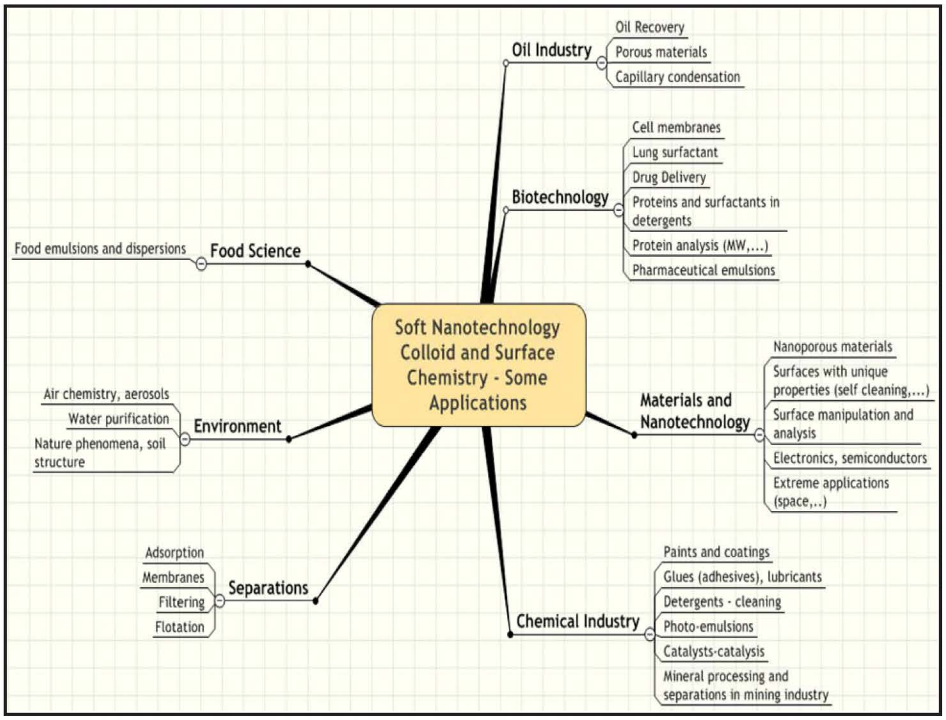

Figure 2. *Selected applications of Colloid and Surface Chemistry.*

stability can be modified (qualitatively), and the "other" non-DLVO stabilization mechanisms due to hydration and steric forces; a bit on kinetics of aggregation

12. *Basic tools for studying emulsion stability and link to DLVO*

In addition, in a short course with emphasis on applications we have found it difficult to include lengthy derivations such as those in surface thermodynamics (for the Gibbs adsorption equation) and those related to charged interfaces. The final results were, of course, thoroughly discussed also via numerical examples exercises, both in the classroom and homework problems. Table 2 shows the various types of exercises used, fulfilling different goals, covering aspects from very simple, straightforward demonstrations all the way to more complex synthetic problems—including a few inspired from industrial applications and projects.

TEACHING METHODS

The weekly 4-hour segments for a 5-ECTS-point course at DTU present a challenge but also a gift for planning the learning activities. Obviously it is impossible to give a straight 4-hour lecture. On the other hand, the sessions offer the opportunity to spend time with students and incorporate more dialogue and interactive learning activities, where the students will become active participants and not simply passive listeners (as in a traditional lecture). We have experimented with different teaching methods in this environment and have arrived at the conclusion that variation and mixture of various methods can give a positive learning environment. It is very important, however, to explain to students what to expect, because unnecessary roadblocks to learning occur when student expectation is not met. In the following section we discuss various elements which have been tested in our teaching of this course.

TABLE 2
Different Categories of Exercises Used in Class or Homework Problems

Exercise Category	Some Examples
1. Simple calculations; Demonstrations based on few experimental data	Adsorption from solution—role of solvent • Competitive adsorption of surfactants on solids • Vapor pressure of droplets via the Kelvin equation • Estimating surface tension via capillary rise • Avogadro number from Brownian motion data • Free energy, enthalpy, and entropy changes in micellization from CMC-temperature data • Debye lengths of single and mixed salts (for aqueous colloids) • Zeta potential via electrophoresis and Huckel/Smoluckowski equations • Hamaker constants for colloidal particles in various media • Heat of adsorption from adsorption data • Spreading of liquids and works of adhesion and cohesion • Molecular weight (MW) of proteins from sedimentation (equilibrium or velocity) data
2. Derivations	Molecular weight equation from gravity or centrifugal measurements • Stokes-Einstein equation and Brownian distance • The maximum of the work of adhesion from Zisman plot • Link of critical and solid surface tensions from interfacial theories • Contact angle via combining Young equation and interfacial theories • CPP (critical packing parameter) of spherical micelles, and the aggregation number of SDS (Sodium Dodecyl Sulphate) • From adsorption theories to surface tension/concentration equations and vice versa—derivation of the two-dimensions ideal law • The general equation for the Debye length as a function of valency, temperature, and medium and specific cases for aqueous solutions at 25 °C • CCC (Critical Coagulation Concentration) via the DLVO theory and surface potential at CCC
3. Group contribution (GC) methods; Estimations via theories	Surface and interfacial tensions of liquid-liquid interfaces, *e.g.*, water-alkanes (aliphatics and aromatics), glycol-alkanes, mercury-water, or hydrocarbons via the Fowkes, Girifalco-Good, and Hansen theories • Estimation of the dispersion part of the surface tension of water • Surface tensions via Parachor and corresponding states methods • Surface tensions via Hamaker constants • Resistance of adhesive points in presence of liquids via the Owens-Wendt theory • Solid surface tensions via contact angle data and a theory, *e.g.*, Owens-Wendt • HLB (Hydrophilic-Lipophilic Balance) of surfactants for use in emulsions via the GC method of Davies-Rideal
4. Inspired from industrial problems	Adhesion in silicon-epoxy coatings via the van Oss-Good theory • Stability of Alumina particles in various media using Hamaker constants alone • Composite and individual adsorptions of solid pigments in paints via Langmuir's equation • Kinetics and creaming of emulsions • Stability (electric vs. steric) of latex paints and kinetics of destabilization
5. Requiring graphical solutions and extrapolations	MW of biomolecules (proteins) via surface pressure-area data • Kinetics of aggregation via particle-time data • MW of polymers from osmotic pressures • MW of colloid particles via sedimentation coefficients • Adsorption, area/molecule, and CMC from surfactant solutions from surface tension-concentration data • Adsorption of gas on solids from volume-pressure data using Langmuir and BET → calculation of specific area of solid • Adsorption of compounds from solution on solids from adsorption-concentration data → calculation of area of adsorbed compound
6. Combined and general	Characterization and wetting of polymer surfaces, *e.g.*, nylon, PET, and Teflon (critical surface tension, Zisman, contact angle, theories, work of adhesion) • Stability of colloids (potential-distance, potential energy-distance curves, Debye length, zeta potential, Schulze-Hardy rule, and CCC • Kinetics of aggregation of (hydro)sols (half-life time, Phase Inversion Temperature for emulsions, stability ratio)

A central component in the course is the variety of teaching methods/approaches employed. Such variety has been considered necessary both for enhancing understanding and for making best use of time within the 4-hour modules used at DTU. The teaching methods we use include:

- *Traditional elements such as lectures and problems*
- *Active individual and group work*
- *Special features to raise interest of students*

(i) *Traditional elements: short lectures with exercises solved by the individual student, with an appropriate choice/balance between exercises suitable for in-class work and homework.*

(ii) *Active individual work or group work on selected topics (see later). Active discussion during the exercise section is absolutely necessary and we find it necessary that both the teacher and teaching assistant are present.*

(iii) *Special features designed to spur and raise the student interest in the topic: these include "the question of the day" (Table 3), guest lecturers and company visits (*e.g.*, a visit to Novozymes for surfactant-enzyme-based detergents or a guest lecture related to the link of fuel cells with colloid stability). The question of the day was an initiative aimed at putting one simple and relevant question to which all students could more or less directly relate, as a headline for each 4-hour session.*

For the group-work sessions, suitable topics have been chosen, *e.g.*, electrokinetical phenomena, electric double layer, and colloid stability. In small groups the students are encouraged to read short parts of the textbook and slides and then discuss the topic among themselves, answering well-defined but general questions given in advance. A discussion in plenum would follow. For example, in the case of "electrokinetical phenomena as used in colloid chemistry," these questions "to inspire the group work" can be:

- *What are they?*
- *How do they work?*
- *Which of them is the most important in your opinion?*
- *What do they measure?*
- *What do they tell us and how are they used in practice?*
- *What are the limitations?*

We soon realized that a 5-ECTS-point course cannot cover both the theoretical and the experimental aspects of Colloids and Interfaces and thus a laboratory exercise course, which runs during January (duration: three full weeks) following the theory course, has been established. Despite the fact that one might have expected a laboratory course to have been as popular (if not more so!) than a theory course, in practice we have observed the opposite, for reasons not entirely clear to us. To make the laboratory course more attractive to students, we have tried to illustrate the "evident" links between theory and laboratory courses as well as a clear illustration of how, in colloid and surface science, theory and experiments go hand-in-hand and little can be said and done without well-defined and planned experiments. Theories and concepts are, of course, useful in this planning and in understanding the results. Table 4 (next page) summarizes these links.

TABLE 3
"The question of the day" (Autumn 2003)

Day	Question
1	How can mosquitos walk on water?
2	Do detergent companies cheat us?
3	What is common for the leaves of lotus and wings of butterflies?
4	Why is it so difficult to paint Teflon?
5	How do you make good bread—or, what is gluten?
6	Why were PEG (polyethylene glycol) solutions used for the conservation of the wooden VASA ship in Stockholm, Sweden?
7	Why is the sky blue but the sunset red?
8	What do milk, mayonnaise, and shampoos have in common?
9	Why—where—what about enzymes?
10	In which three ways can you measure the molar mass of colloids?
11	When is a colloidal suspension stable—above or below the critical coagulation concentration?
12	What is the most important thing you have learned about colloidal and surface chemistry, and how is it relevant to you in practice ?
13	Why do plastic paint buckets always have dusty lids?
14	Why does the bathroom mirror always steam up?
15	What makes a no-stick frying pan no-stick?

STUDENT EVALUATION, CONCLUDING REMARKS, AND SOME SUGGESTIONS

Student satisfaction with the course has been high despite the difficulties associated with finding an appropriate textbook for our needs. Greater satisfaction with the course material evident in recent years could be attributed to the availability of extensive slides from the lecturers in the form of PowerPoint presentations with Notes. Our experience from teaching Colloid and Surface Chemistry in a mixed student audience with different expectations, interests, and directions has been presented. We have discussed curriculum, textbooks, and learning objectives emphasizing the "unifying concepts" that can enhance understanding. Despite the numerous textbooks available, we feel that only a few cover both topics in substantial detail and at a level suitable for undergraduate students.

REFERENCES

1. Pashley, R.M., and M.E. Karaman, *Applied Colloid and Surface Chemistry*, Wiley (2004)
2. Shaw, D., *Introduction to Colloid & Surface Chemistry*. 4th Ed., Butterworth-Heinemann (1992)
3. Goodwin, J., *Colloids and Interfaces with Surfactants and Polymers: An Introduction*, Wiley (2004)
4. Jonsson, B., B. Lindman, K. Holmberg, and B. Kronberg, *Surfactants and Polymers in Aqueous Solution*, Wiley (2001)
5. Hamley, I., *Introduction to Soft Matter. Polymers, Colloids, Amphiphiles and Liquid Crystals*, Wiley (2000)
6. Hunter, R.J., *Introduction to Modern Colloid Science*, Oxford Science (1993)
7. Hiemenz, P.C., and R. Rajagopalan, *Principles of Colloid and Surface Science*, 3rd Ed., Marcel Dekker (1997)
8. Israelachvilli, J., *Intermolecular and Surface Forces*, Academic Press (1985)
9. Barnes, G.T., and I.R. Gentle, *Interfacial Science—An Introduction*, Oxford University Press (2005)
10. Myers, D., *Surfaces, Interfaces, and Colloids: Principles and Applications*, VCH, Weinheim (1991)
11. Woods, D.R., and D.T. Wasan, "Teaching Colloid and Surface Phenomena," *Chem. Eng. Educ.*, **30**(3) 190 (1996) ❐

TABLE 4

What can/should be measured and what can be calculated in "Colloid and Surface Chemistry"?

Property	**Can we measure it? How?**	**Can we estimate it? How?**	**Comments/Importance**
Surface tension of pure liquids and liquid solutions	X (Du Nouy, Pendant Drop, Wilhelmy plate, capillary rise)	X (Parachor, solubility parameters, corresponding states)	Wetting, adhesion, lubrication, . . .
Interfacial tension of liquid-liquid interfaces	X (Du Nouy)	X (many methods, *e.g.*, Fowkes, Hansen, Girifalco-Good)	Surfactants, . . .
Surface tension of solids		X (Zisman plot, extrapolation from liquid data, solubility parameters, parachor)	Wetting, adhesion, . . .
Interfacial tension of solid-liquid and solid-solid interfaces		X (many methods, *e.g.*, Fowkes, Hansen, van Oss-Good)	Wetting, adhesion, characterization and modification of surfaces, . . . (paints, glues, . . .)
Contact angle between liquid and solid	X (many goniometers and other methods)	X (combination of Young equation with a theory for solid-liquid interfaces)	Wetting, adhesion, characterization and modification of surfaces, . . .
Critical micelle concentration of surfactants	X (change of surface tension or other properties with concentration)		Detergency, . . .
Surface or zeta potential of particles	X (micro electrophoresis)		Stability of colloidal dispersions
Adsorption of gases/ liquids on solids	X (many methods)	X (many theories, *e.g.*, Langmuir, BET, Freudlich)	Stability, surface analysis
Topography of a surface	X (AFM, STM)		Surface analysis and modification
HLB (Hydrophilic-Lipophilic Balance)		X (group contribution methods, solubility parameters)	Design of emulsions including stability of emulsions and determining the emulsion type
Work of adhesion	X (JKR, AFM)	X (the ideal one via Young-Dupre and similar equations)	Adhesion, detergency
Interparticle forces and colloid stability	X (surface force apparatus, AFM, and other methods for stability, *e.g.*, Turbiscan)	X (DLVO theory)	Stability of all types of colloids (paints, food colloids, . . .)
Molecular weight of polymers and proteins	X (many methods, *e.g.*, ultracentrifuge and osmotic pressure)		Characterization of high-molecular-weight molecules
Creaming and sedimentation of suspensions and emulsions	X (Turbiscan)	X (Stokes equation for dilute dispersions)	Stability of colloids
Critical Coagulation Concentration	X (series of experiments adding salts in colloidal dispersions until coagulation occurs)	X (DLVO theory)	Stability of colloids
Determining emulsion type		X (HLB and Bancroftt rule)	Emulsion design