Building classical coherence into a quantum chemistry course: A case study of improving constructive alignment in a multi-teacher setting

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Introduction

Advanced Quantum Chemistry (KemiVK) is an elective course at the Department of Chemistry at the University of Copenhagen, taken for the most part by chemistry and nanoscience bachelor students at the end of their second year. It is a small course, with fifteen to twenty-five students in a typical year, and it has been taught for many years by very experienced lecturers to consistently good reviews. What makes the course particularly interesting from a pedagogical point of view is that it is assembled from several rather different parts: classroom lectures that alternate both topics and lecturers week by week, multiple sets of lecture notes and textbook excerpts, weekly exercise classes built around a problem collection, a handful of applied computational workshops, and, at the end, a thirty-minute oral examination. I had previously served as teaching assistant for the course's exercise classes. This year I took on a different role, as the main lecturer for one quarter of the lecture series, namely four three-hour blocks over two weeks, and it is the design and delivery of that section, together with my attempt to evaluate it, that I present in this work.

The core challenge: weaving many parts into one coherent thread

My interest in the challenge of enhancing congruence in this course arose during the term I spent as the course's teaching assistant. Observations during the exercise classes suggested that, while the course's individual elements were each reasonably well matched to the intended learning

outcomes, the coherence between different parts could be improved (Hounsell & Hounsell, 2007). The classes, the two older sets of lecture notes that were provided as course material, and the problem sets each carried their own notation and their own presentation style, with the result that a student could meet an idea in one place and then fail to recognize it in another. In a subject like quantum chemistry, where many ideas are quite abstract in nature and rest on the understanding of threshold concepts that reorganize how a student sees the field once they are grasped (Meyer & Land, 2006), incoherence in teaching materials adds a difficulty that has nothing to do with the underlying course content and that could thus be reduced. Constructive alignment offered the natural frame for redesigning a section of the course: the principle that intended outcomes, teaching activities and assessment should be brought into coherence with one another, so that what students are asked to do, and how they are judged, both point towards the same goals (Biggs, 1996; Biggs, Tang & Kennedy, 2022). Cognitive load theory suggests that a consistent notation, and the pruning of long, mechanical derivations, reduce the extraneous demands on working memory and leave more of it free for the genuine difficulty of the material (Sweller, van Merriënboer & Paas, 1998). Research on worked examples points in the same direction, showing that several varied examples which make the underlying structure visible help learners build the schemas that expertise depends on (Atkinson, Derry, Renkl & Wortham, 2000). And the coherence and signalling principles of multimedia learning provided good reason to add explicit road maps and summaries, and to leave unnecessary details out (Mayer, 2009). These principles guided the redesign of the lecture blocks and the development of an accompanying set of lecture notes, as described below.

Designing the course section: classroom teaching and lecture notes

I was given the topics for the four blocks in advance, and all of them belonged to the curriculum I was required to cover: the variational method, perturbation theory and the Hellmann–Feynman theorem in the first week; spin orbitals, many-electron wavefunctions and Slater

determinants, the Slater–Condon rules, and second quantization in the second. My aim was to design the four classroom blocks and an accompanying set of lecture notes as a single, coherent whole rather than as multiple separate artefacts. The problem sets were deliberately left unchanged, as the exercise classes were taught by another instructor. Revising them unilaterally would have risked introducing precisely the kind of mismatch the redesign aimed to remove.

Some design choices I made carried across the entire section I taught. I opened each block by stating the learning outcomes it served, so that students could see from the outset what the goal of the session was. My overarching aim was to enhance conceptual understanding building on cognitive constructivism and focusing on the levels “understand”, “apply”, and “analyze” from Bloom’s revised taxonomy of learning (Anderson & Krathwohl, 2001), as these corresponded precisely to the the course's intended learning outcomes and also the skills that had to be demonstrated in a successful oral exam (Biggs, 1996; Biggs, Tang & Kennedy, 2022). In the previous year, when teaching the exercise classes, I observed that some students struggled with taking the step from understanding the theoretical concepts in the lectures to applying them in practice when solving problem sets themselves. To reduce this hurdle from “understanding” to “applying”, I decided to incorporate illustrative examples in the lecture, such that new concepts and methods were not merely just introduced in a general but non-tangible manner, but also directly put into practice during the lecture by working through their application based on a problem that the students were already familiar with from earlier courses or previous sessions (Koedinger, Rau & McLaughlin, 2023). I carried the same worked examples from the lectures into the lecture notes, so that the written material would reiterate what had happened in class rather than recast it in an unfamiliar form. Throughout, I kept to one notation and one language instead of the former mix that was used in the previous set of notes. Each section of the notes closed with a short summary of the key takeaways, followed by suggestions for further reading, thereby showing consistency also in the formal structure of the lecture notes.

Beyond these common threads, the two teaching weeks called for rather different strategies. In the first, which dealt with the variational and

perturbative approximation methods, I sought alignment through parallelism. I structured the two methods in the same way: introducing each in turn and illustrating each on a worked example that was already familiar to the students, the particle in a box for the variational method and a linearly perturbed harmonic oscillator for perturbation theory, and then drew them together, comparing the two both in general terms and as applied to a single shared example, the helium atom. The deliberate symmetry was the point: presenting the two methods through the same moves applied to familiar problems, and then explicitly setting them side by side, was meant to let students see them as two instances of one larger idea rather than as two unrelated concepts (Atkinson, Derry, Renkl & Wortham, 2000).

The second week was harder to unify because the curriculum topics are more numerous and diverse. Here I tried to supply the thread connecting the different concepts myself through a more narrative design. I gave a road map, presented both in class and at the head of the lecture notes, of what we would cover and why; and I introduced each section out of the one before it, motivating the next step from the last, so that the sequence of topics would appear as logical blocks building on top of each other rather than a loose list of topics (Mayer, 2009). I also tried to connect new topics to the previous ones by revisiting familiar concepts, for instance by re-deriving the Slater-Condon rules also in second quantization after having introduced this framework as a way to recast the entire many-electron formalism in a more convenient way, thereby repeating the key derivation steps while allowing for direct comparison of the mathematical consequences when using the first- versus the second-quantized formalism.

To enhance student learning, I chose to release the lecture notes only after each class. I wanted students to follow the derivations live, and to let some of the results, particularly the cases where an approximation does better or worse than intuition would suggest, come as a small surprise before the answer was available in writing, as an example of constructive friction (Vermunt & Verloop, 1999). I told students in advance that a set of lecture notes would be made available such that they could follow the lecture more closely instead of focusing primarily on note-taking, and most seemed content with that arrangement.

Evaluating the redesign and its effects

Four sources of evidence were used to evaluate the redesign: a structured comparison of the new and previous lecture notes (Table 1); my own observations of classroom engagement; the standard end-of-course evaluation, including free-text comments; and examination completion and grade data. Because the course evaluation covers the course as a whole, these sources are interpreted as indicative rather than conclusive.

The most important difference in coherence of the redesigned course section lies in how closely the written material now follows the classroom teaching. The previous set of notes omitted some topics altogether and treated the others in a framing only loosely related to how they were introduced in class; the new lecture notes, by contrast, cover exactly the content that was taught, in the same framing, with any additional material clearly marked as an excursus. Beyond this, and as the comparison in Table 1 sets out, the new set of notes differs from its predecessor not just in its content but also in its design: a single notation in place of several, methods illustrated through worked examples rather than merely stated as results, explicit learning outcomes summarized as key takeaways, and road maps and section linkers where the older notes were terse and reference-like.

Table 1. Comparison of the previous and the new lecture notes based on design and alignment with the class.

Criterion	Previous set of notes	New lecture notes
Alignment with classroom teaching	Some topics absent altogether; those present only very loosely matched how the material was presented in class	Covers exactly the content taught, in the same framing; any additional material clearly labelled as an excursus

Notation and language	Notation varies across topics; mixed Danish/English sections	Single unified notation and language throughout
Worked examples	Few; definition- and derivation-led	Each method illustrated on a concrete, already familiar example
Structure and navigation	Reference style; front-loaded definitions	Road maps linking sections; key takeaways and further reading suggestions closing each section
Derivations	Mix of full derivations and pure result statements	Longer derivations trimmed; context and intuition added
Intended use	Standalone reference material; legacy lecture notes	Coherent post-class reference paired with the current lectures

How much the redesign of my section helped students is harder to establish, since I taught only a quarter of the course and cannot isolate the impact of my part in the formal assessment instruments. By my own reading of the classroom, the first week of lecture blocks worked as intended: the students actively followed the derivations and built the comparison of the two methods with me at the board, with broad classroom engagement. The overall course evaluation was positive on the design dimension the project targeted: 72% found the course's elements coherent, 86% felt they had acquired the stated competences, and every respondent judged the teaching material relevant. Free-text comments on this section referred specifically to the features central to the redesign: the worked examples, the end-of-week comparison of methods, the opening

road map, and the lecture notes released after class, which several found helpful in preparing for the exam. For instance, one student commented

> "Really nice and structured lectures, especially nice with all of the examples. She managed to present the basics and build them up to the harder concepts in a way that made it easy to follow. Great lecture notes, very much appreciated."

However, the same student evaluations also clearly mark the project's limitations and shortcomings. By my own judgement, echoed by a student, the second week was weaker than the first: where the worked examples thinned and the pace rose, coherence decreased. And although my section kept to one notation, the students' most frequent request in the course evaluation was still for a consistent notation across the course's several parts, a problem compounded this year by having four lecturers rather than just the two of previous editions. As one student said "It may not have been the case for previous years, but I think having four different lecturers made it harder to follow the course because the notations used by each person were not always consistent.", which serves as a strong reminder that congruence is felt course-wide and cannot be ensured just section by section.

Examination records provide a final, limited indication. The average grade remained unchanged compared with previous years, while the completion rate, typically 80–90% in earlier editions, reached 100% (26 of 26 enrolled students, the largest cohort to date). While it is impossible to disentangle the effects of different changes in this year's course, it can be taken as a positive sign that despite having even more different lecturers with their individual styles and deviating notations, overall, it was a course worth seeing through.

Discussion

The outcome of this project offers three implications that reach beyond the redesign of a section of this single course. The first concerns the course design itself when addressing the middle layers of Bloom's taxonomy of learning: coherence felt high in the week where worked examples were plentiful and loosened where they were sparse. Consistent

with the worked-example and cognitive-load literature (Atkinson, Derry, Renkl & Wortham, 2000; Sweller, van Merriënboer & Paas, 1998), this suggests that for material of this difficulty and abstract nature, the worked example is not merely an illustrative add-on, but the load-bearing link between lecture and problem solving in practice, enabling the students to make the step from "understanding" to "applying" (Anderson & Krathwohl, 2001; Koedinger, Rau & McLaughlin, 2023).

The second key point concerns the level at which coherence can be engineered. The evaluations show that congruence is experienced across the whole course, yet the project I conducted only impacted one section, and a single consistent notation within it did not remove the seams students met at the boundaries with other teachers (Hounsell & Hounsell, 2007). In a multi-teacher course, ensuring constructive alignment is therefore only partly an individual task, and the arguably bigger challenge is to establish a shared notation and a common reference text agreed across the entire teaching team.

The third overall takeaway from this project is that pedagogical choices often trade off against one another rather than admitting a single right answer. The delayed release of the lecture notes creates constructive friction for some students (Vermunt & Verloop, 1999) but withholds a resource from others who prefer to read ahead. In future editions of the course, such tensions could be discussed explicitly and managed better, for instance by circulating an outline of the content and further reading recommendations in advance, while reserving the worked examples for an in-class demonstration and thus only providing the corresponding reference material afterwards.

Conclusion

This study examined whether the coherence of a multi-component quantum chemistry course could be improved through the redesign of a single section. Within the single section I was given, I redesigned four classroom blocks and wrote an accompanying set of lecture notes as one coherent whole: organised around explicit learning outcomes, carried by worked examples that move students from understanding a method to applying it, and held together by a single notation and a connecting road

map. The evidence I could gather, namely the redesigned material compared against the previous set of notes, my own reading of the two weeks, the formal evaluations, and the examination results, converges on a cautiously positive conclusion: coherence within the redesigned section improved, particularly where alignment through parallelism was pursued.

At the same time, the project also illustrates the limits of what a single lecturer can achieve in a multi-teacher course. The redesign strengthened coherence within the four lecture blocks concerned, but section-level alignment alone could not produce the seamless course experience that students evidently value. More generally, the project translates the broad aim of improving coherence into a set of concrete, transferable design principles: making learning outcomes explicit, using recurring worked examples to link theoretical concepts to problem solving, maintaining a unified notation, and pairing classroom teaching with reference material written to match it. These principles can be refined further within individual course sections, but the findings indicate that the greater gains are likely to come from coordination across the teaching team, in particular through an agreed common notation and shared reference material for the course as a whole.

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