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The Making of Contemporary Physicists: Figured Worlds in the University Quantum Mechanics Classroom

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Introduction

This paper concerns the re/production of norms about physics teaching and learning in a Swedish university quantum mechanics classroom. The university teachers in the analysed classroom can be characterised as implementing reform-based physics teaching, inspired by physics education research they aim to realise a classroom with a high degree of active student participation. The students are all majoring in physics, a minority on route to becoming high school physics teachers. The main focus of the paper is the teaching choices made by the university teachers and the student identity positions made possible by these choices, but potential consequences for physics teacher education will also be discussed.

Traditionally, physics education research has been primarily concerned with students' conceptual understanding, but the field has expanded to include a rich array of cognitive as well as social aspects of the teaching and learning of physics (Beichner 2009). Research on quantum mechanics has shown that this area has specific difficulties for students that distinguish it from classical mechanics (Dreyfus et al. 2017), such as probability (Marshman and Singh 2017) and quantum measurement (Zhu and Singh 2012). Further, students sometimes mix conceptions from

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classical mechanics and quantum mechanics (Petri and Niedderer 1998). But not only does quantum mechanics present particular difficulties to students, it is also a high-status subject within physics educations (Johansson 2015). Johansson et al. (2018) argues that quantum mechanics has a special cultural significance for physics students, not only because of its central role in the physics curriculum as such but also because of its prominent place in popular culture and the history of physics. Consequently, Johansson et al. (2018) argues, students invest highly in the first quantum mechanics course, but 'even successful and motivated students struggle with making sense of their expectations and experiences of quantum mechanics'. A reason for it has been argued to be that the opportunities for being 'a good physics student' in introductory quantum mechanics courses are limited to being good at calculating (Johansson 2015). Instead, most quantum mechanics courses have de-emphasised interpretational issues and instead focused on the mathematical aspects (Kaiser 2002). However, there are also multiple studies seeking to develop different teaching and learning practices for the quantum mechanics classroom (Zollman et al. 2002; McKagan et al. 2008). For example, Bøe et al. (2018) have studied the implementation of an innovative quantum mechanics teaching approach in upper-secondary school, focusing on potential tensions between this approach and a traditional physics teaching approach. They found that the students were socialized into a traditional physics teaching culture and that this framed their experiences of the new teaching approach. The students easily adopted aspects of the innovative approach that allowed them to participate in physics teaching and learning in ways that resembled what they were used to from traditional physics classrooms. However, the students struggled with how to monitor their progress in the absence of calculations and correct answers. A difficulty to break traditional patterns of teaching and learning in university physics classrooms, where teacher-centric teaching tend to be the norm (Höttecke et al. 2012), was found by Carlone (2004) and Hasse (2002). Carlone (2004) found that even in a classroom where pedagogical innovations were valued, students and teachers reproduced physics as 'difficult' and a subject where 'raw talent' is needed. Moreover, despite seeking to develop a classroom of active student participation, the good student was reproduced as a listener, memoriser and recipient of knowledge. Similarly, Hasse (2002) found that implicit and explicit messages about 'the good physics student' were not always consistent in the physics classrooms she studied; while students were told to follow instructions during practicals, deviating from these were valued by the university teachers and students who did so were seen as creative and potential future physicists.

In the classroom studied in this paper, a minority of the students are on route to becoming physics teachers. While the quantum mechanics course does not include the teaching and learning of physics as a course content, what is explicitly and implicitly communicated about teaching and learning is highly relevant for the future physics teachers. This is particularly interesting as previous research show that physics teacher education is often fragmented, as different departments are responsible for different parts of the education (Larsson et al. 2018). It is in the light of the need to create a better continuity across different part of the physics teacher education (Sandifer and Brewe 2015) we discuss the potential consequences of our findings for teacher education.

Research Questions

- What norms about physics teaching and learning are reproduced and contested in the quantum mechanics teaching of a reform-based physics course?
- Which physics student identities are endorsed in this reform-based physics course?

- What are the potential consequences of the findings for physics teacher education?

Analytical Framework

Figured Worlds

In conceptualising the social practices of the quantum mechanics classroom, we find the concept of *figured worlds* as developed by Holland et al. (2001) useful. A figured world is culturally constructed 'realm of interpretation in which a particular set of characters and actors are recognized, significance is assigned to certain acts, and particular outcomes are valued over others' (Bartlett and Holland 2002, p. 12); that is, certain identity performances will receive positive recognition by, for example, peers or teachers. Hence, a figured world includes assumptions about what is considered typical and atypical, thus re/producing power relations between different ways of acting. As such, figured worlds are simplified models of some aspects of the real world, and encompass taken-for-granted stories about how the world functions (Holland et al. 2001). There is a reciprocal relationship between figured worlds and experiences; experiences re/shape figured worlds, but our figured worlds also colour our interpretation of experiences (Lock and Hazari 2016). In this study, figured worlds are used as a means of understanding enactments of the social practice of the quantum mechanics classroom and the concomitant student identities.

Identity

Within a social context, there are recognisable ways of being—intelligible identities (Butler 1999)—and social pressure to conform to particular norms. In the context of university studies, students are also involved in constructing social identities as legitimate members of a discipline (Søndergaard 2002). An intelligible identity is one that re/produces certain normative values and relations (Butler 1999). Carlone and Johnson (2007) propose that science identity can be understood as being made up of competence, performance and recognition. Hence, it is not enough to self-identify as a particular kind of person (a biologist or a future research scientist); it is also important that these performances are recognised by other actors within the community. Identities are enacted within and through figured worlds by making use of the resources available within this figured world. We are interested in which identity performances are rendered intelligible in the studies' classrooms, and thereby recognised as appropriate and possibly also valorised.

Data Collection, Research Context and Analytical Process

This paper utilises empirical data consisting of observations of two physics university teachers' teaching, informal interviews with both physics university teachers, carried out in connection with the observations, and two longer semi-structured interviews with one of the teachers (approximately 60 min each). The teaching observed was an introductory quantum mechanics course for physics majors, at a large, research-intensive Swedish university. The course has undergone substantial pedagogical development and can be considered to represent 'reformed' physics teaching, with a strong focus on student activity. While all the students ($N = 30$) were majoring in physics, they specialized in different fields such as experimental and theoretical physics, and meteorology. The course was also attended by students studying to become high school physics teachers. In terms of content, the course can be considered a rather typical introductory quantum mechanics course, dealing with topics such as historic background to quantum mechanics and basic concepts and methods within quantum mechanics (e.g. the Schrödinger equation, the uncertainty principle, and the harmonic oscillator). We have carried out observations during three iterations of the course, with a focus on the introductory sessions, as these are when the teaching and learning approaches of the course are explicitly discussed and established. In total, the course included approximately 15 seminars (two hours each), followed by problem sessions (2 h each). During the first iteration of the course, two seminars were observed, during the second iteration one seminar, and during the third iteration four seminars. The course was taught by the same two university teachers during all three iterations, here called Lina and David.

During the seminars, Lina and David practiced co-teaching, taking turns in the lecturing and engaging in dialogue with each other during the teaching. They also made use of *clickers* in the teaching, a personal response system that allows students to give individual responses to multiple-choice questions (cf. Deslauriers et al. 2011). Each seminar was started off by clicker questions, followed by a short lecture, and finally group work.

All seminars were observed by two researchers, and documented using field notes. The interviews with Lina were audio-recorded and transcribed. The project adheres to the The Swedish Research Council's (2017) ethical guidelines. Data excerpts have been translated from the original Swedish, with the aim of capturing meaning and edited slightly to enhance readability.

The analysis of the empirical data commenced by repeated readings of the data as a whole focused on how the teaching and learning of quantum mechanics was staged in the studied classroom. This preliminary analysis highlighted tensions and alignments between the physics teaching the university teachers tried to implement in their classroom and what was perceived as traditional means of physics teaching. In order to systematize the exploration of these tensions and alignments, the next step of the analysis was guided by the framework of ‘figured worlds’, thematising the empirical data in terms of the ‘taken for granted stories’ within different figured worlds. Thereafter, the internal logic of the different figured worlds was scrutinized in more detail by considering ‘how power relations between different ways of acting’ within figured worlds are produced (Holland et al. 2001). Finally, physics student identities endorsed within each figured world were analysed.

Findings

The Figured World of Classroom Quantum Mechanics

The course we have observed is an introductory course in quantum mechanics, but given the subject’s status within the discipline of physics (Johansson et al. 2018), the students are likely to have a prior relationship with the subject. Hence, when Lina and David introduce the subject, they are not only introducing their view of quantum mechanics, but also responding to the students’ preconceptions about quantum mechanics. As such, Lina and David can be understood as construing a figured world of classroom quantum mechanics that adheres to broader cultural notion of quantum mechanics. When the students first enter the quantum mechanics classroom, they are met by a projection of a Powerpoint slide showing a cartoonish representation of quantum mechanics, with a speech bubble saying: ‘This shit is crazy! It’s crazy’. (Field notes, observation, year 3, session 1.) The potential counter-intuitiveness of quantum mechanics was something Lina and David returned to on several occasions during the observed teaching:

> Lina: ‘How many find this to be counter-intuitive and weird?’ One student raises a hand. Lina: ‘Those of you who don’t raise your hands probably need to give this some more thought, ‘cause this is weird.’ (Field notes, observation, Year 3, session 2)

Thus, the students cannot expect to understand quantum mechanics, and Lina and David noted that the students are in good company if they find the indeterminism of quantum mechanics unsatisfying:

> Lina: ‘If you find this unsatisfying, you’re not the only ones. We have a theory that doesn’t explain. Einstein didn’t believe in this. You’re in good company.’ (Field notes, observation, Year 2, session 1)

Consequently, not understanding and finding quantum mechanics ‘weird’ or even ‘crazy’ are construed as something typical within the figured world of quantum mechanics, and, hence, becomes part of the taken-for-granted story about this disciplinary field. Thereby, a power relation between different ways of acting is also produced: the physicist-to-be needs to accept quantum mechanics as being counter-intuitive, and if someone does not consider quantum mechanics to be weird and counter-intuitive, it is because they have not grasped the full complexity of the theory. Here the university teachers are presenting an opportunity to the students to be recognised as physicists by them acknowledging the full complexity of the disciplinary area they are about to enter. In addition, the repeated references to Nobel prizes construes quantum mechanics in particular, and physics in general, as high-status areas. However, the remaining questions concerning quantum mechanics, how the theory in some sense is unfinished (‘what actually happens when the wave function collapses is still an unsolved problem’ (field notes, observation, year 3, session 1)), is also presented as tantalising, something that could be an interesting research topic. The physics students are, as such, expected to be fascinated, rather than scared, by the unfinishedness of quantum mechanics and the high status of the field. Quantum mechanics is also construed as beautiful, and significance is assigned to the aesthetic qualities of the mathematical formalism:

> Lina continues to write formulae on the black board and says: ‘This surely is stunning!’ She continues with emphasis: ‘Note how beautiful this solution is!’ (Field notes, observation, Year 1, session 1)

The importance of the aesthetic qualities becomes part of the taken-for-granted story about quantum mechanics, something the apprentice physicist is expected to be able to appreciate. Further, the perceived difficulty and counter-intuitiveness of quantum mechanics is alleviated by the linking of quantum mechanics to previous knowledge areas the students are assumed to be familiar with. For example, Lina and David discuss how Newton’s equations can be derived from quantum mechanics and make links to the students’ previous experiences of probability and linear algebra, and the usefulness of those fields for quantum mechanics. The difficulty and counter-intuitiveness of quantum mechanics is also mitigated by assurances that while the mathematics can get seemingly complex, the procedure as such is simple:

> David continues the explanation of how the time-dependent Schrödinger equation is solved and says: 'It can become a large [mathematical] expression, but the procedure is simple.' (Field notes, observation, Year 3, session 3)

Overall, quantum mechanics is construed as a high-status discipline that is difficult and counter-intuitive, but also exciting and beautiful and at least partly accessible through previous mathematical knowledge and the application of simple mathematical procedures. These different facets of the figured world of classroom quantum mechanics can be understood as different resources made available for the students for constituting identities as physicists. An intelligible physicist identity can, thus, be performed by the student in this classroom by utilising these resources.

The Figured World of University Physics Teaching and Learning

During our first meeting with Lina and David, they explained that they had received pedagogical development funds to develop the teaching of quantum mechanics, since it is a subject that contains many new concepts, is not intuitive and is difficult for the students to understand. Their pedagogical development drew heavily on the work of Carl Wieman and colleagues (informal interview, prior to observation, year 1, session 1). When introducing their pedagogical approach Lina and David pointed out that:

> Everything we do is based in research, in different experiments done. This seems to work well – it's not something we have just made up. (Field notes, observation, Year 3, session 1).

They also made references to physics education research supporting their approach, and David stressed that the use of clickers (Wieman and Perkins 2005) had been developed by a Nobel laureate. Implicitly, this also conveys the notion that the basing of teaching in research is by no means part of the taken-for-granted story about university physics teaching. During the introductory seminars, Lina and David pointed out that their physics teaching is different compared with other physics courses and used approximately the first half an hour to explain how the teaching of the course is organized. Each seminar was started off by a few clicker questions that were then discussed by the whole class, followed by a lecture of about 25 min. Lina and David stressed that the students needed to have prepared well for the seminars:

> The lectures are built on that you have read the preparatory material. We will not repeat it. We assume that you have read. (Field notes, observation, Year 2, session 1).

Once again, by so strongly stressing the importance of reading the preparatory material, the typical physics lecture is construed as one that does not require prior readings, and the implication is also that students do not typically read in preparation for lectures. The physics student identity the university teachers are endorsing is one of well-preparedness, but not only that, the teachers are also appealing to the students' self-governance (Östman et al. 2015) as a certain level of preparation is needed in order to follow the teaching.

The clicker questions were completed by the students individually, without the use of course books or calculators, to assure that the students have in fact done the preparation reading and to monitor student understanding. The clicker questions also account for part of the examination of the course; correct answers could give a student an additional 20% on the final exam. It can also be noted that the university teachers repeatedly point out that the multiple-choice questions can have more than one correct answer, thereby implying that this is not usually the case for physics questions. Further, most clicker questions could be answered without making calculations, and during the individual interview Lina explained that physics teaching traditionally has focused a lot on calculations (in line with Johansson 2015):

> And we might not focus so much on it because there are some things that feel so obvious to us who use these concepts daily and have thought about them for many, many years' time and then we think that it's something that is pretty easy for the students to gain a good understanding of. So that they are kind of mentioned in a sub-clause, and then there a lot of focus on calculating stuff. (Lina interview)

The repeated explanations of how the teaching of the quantum mechanics course is organized and, in particular, how the teaching approach repeatedly is contrasted to what is assumed to be typical for university physics teaching shows that the teaching approach the two observed physics university teachers are trying to implement is by no means something that can be taken for granted. That lecturing is the expected mode of physics teaching is further reinforced by how lectures are positioned as the 'usual' way of teaching and group work as very different from traditional physics teaching and as the 'heavy part' of the course (field note, observation, year 2, session 1). In particular, David focused on the importance of active participation for effective physics learning:

> David presents the basic principle as to why this type of teaching is so efficient. He stresses that it's about active practice – to not come unprepared to the teaching sessions, and continues: 'In small groups everyone has the possibility to contribute.' […] 'We can acquire a maximum of seven new concepts, so the content needs to be limited.' (Field notes, observation, Year 3, session 1)

In the excerpt above, it is also noticeable how the university teachers stress that people are unable to acquire more than seven new concepts at a time. Here, the number of concepts one is able to acquire during a given period is presented as a scientific fact, as above construing the teaching approach as based in research. To actively engage with the physics content is thus construed as the key to efficient physics learning, but this is not just about quality engagement (for example, not handling too many concepts at once), it is also about quantity. Hard work and lots of practice is what is needed in order to master this demanding subject area:

> David: 'If you do not have a talent, anything can be practiced. Practice, practice, practice. And to get feedback. After 10,000 hours you are world class in anything.' (Field notes, observation, Year 2, session 1)

The endorsed physics student identity is, consequently, a hard-working one. Lina elaborated further on this during the interview. She strongly distanced herself from the notion that 'brilliance' or 'talent' is important for the learning of physics. Instead, she focused on hard work as the key to physics learning, also as a means of compensating for poor prior knowledge:

> Well, brilliance, I would not like to… No, I would not like to point out brilliance or talent or, like the most important actually. But, if you have, good previous knowledge and find it easy to learn and the will to spend a lot of time [studying], then you have excellent prerequisites to become very skilled. But, the previous knowledge I think can be bridged quite easily if you are willing to work hard when you get here. (Interview with Lina).

Here, Lina can be understood as challenging a common cultural notion of physics as only available to learners with a particular talent (Carlone 2004), thus producing a power relation between different ways of acting as a physics learner, where hard work is preferable to relying on talent. But, while the idea of the physicist as the lonely genius (Sullivan 1994) is very much challenged, physics is still construed as an individualised endeavour, where the idea of the individual genius is renegotiated into an idea of the individual hard-worker.

Repeatedly, different possibilities within the figured world of university physics teaching and learning are explicitly brought to the fore and contrasted: research-based versus non-research-based teaching approaches, teaching that demands prior reading versus teaching that does not, teaching that focuses conceptual understanding and 'big ideas' versus teaching that is focused on calculations, and lectures versus group work. This contrasting also produces power relations within the figured worlds of university physics teaching and learning, where certain ways of acting are giving prominence over others. The figured world of university physics teaching and learning which Lina and David seek to construe in their classroom is often explicitly contrasted to an assumed taken-for-granted story about traditional university physics teaching, in which the students are passive recipients of a largely teacher-centric teaching that privileges calculations. However, the pedagogical inventions (clickers and group work) are still quite clearly separated from the more traditional lecturing parts of the teaching; every seminar includes an introductory lecture that consists of fairly traditional 'chalk and talk'-physics, with limited student interaction. Further, the group work is predominantly framed as a way for the individual student to engage with the physics content, downplaying the social aspects of learning. The idea of learning as strongly related to individual cognition is also communicated implicitly through the use of clickers as a means of monitoring each student's understanding. The apprentice physicist is expected to devote considerable amounts of time outside of the classroom to quantum mechanics and to take active part in classroom activities.

The Figured World of Professional Physicists

The second part of each seminar, following the short lectures by the university teachers, was organised as group work. Group work was presented as useful both in terms of how it is beneficial for learning and as a means for preparing for how the students can expect to work once they become professional physicists:

> Lina: We had an alumni meeting yesterday. And they said that what they need is to be able to explain to others. Many who work at [a Swedish developer of telecommunications equipment] need that. (Field notes, observation, Year 1, session 1)

Thus, in their classroom, Lina and David are also figuring a world of professional physicists, by explicitly bringing to the fore the qualities expected from a professional physicist. David elaborated further on this, intertwining the usefulness of group working skills for the professional physicist with its usefulness for learning:

> David explains that in most companies, employees work in teams and that this is something – a soft skill – the students are given in the course. (Field notes, observation, Year 2, session 1)

Further, he goes at length explaining that the group work is not assessed and that the group shares the responsibility for creating a good learning environment. Hence, he construes a figured world of student learning that contrast with a focus on performance and solving the problems as quickly as possible, which is a commonly reproduced taken-for-granted story about problem-solving in university physics (Berge and Danielsson 2015). Yet, it can be noted that collaborative work outside of the classroom never is explicitly encouraged. It is continuously stressed that much of the work is to be done at home, but this work is implicitly construed as individual.

It cannot be taken for granted that group working skills are recognised as an important part of the professional physicist's practice, and therefore something that needs to be explicitly established. Here, the ability to work in a group becomes a valorised physicist quality in its own right, and one that the students are expected to develop during the course.

Discussion

The analysis shows that in the observed quantum mechanics teaching, the university teachers continuously negotiate their reform-based teaching in the light of what is construed as a traditional university physics teaching practice. Such teaching tends to be teacher-centric with little active student participation (Höttecke et al. 2012), and when refiguring a different kind of university physics teaching this is something Lina and David explicitly position their teaching in relation to. This is in line with Bøe et al. (2018) who found that students' socialisation into a traditional physics teaching culture framed their understanding of the reform-based physics teaching. In our study, particularly the use of clickers can be seen to occupy an ambiguous position in relation to traditional and reformed versions of physics teaching. While very much gaining their value by being supported by contemporary physics education research (Wieman and Perkins 2005), the use of clickers in this particular classroom is also framed by being part of the assessment; the aim does not become a means of evaluating the teaching in a formative way, but more of a summative assessment of student learning. The difficultly to refigure the use of clickers into part of a formative learning process may, consequently, be a result of this; how much this activity resembles a traditional summative assessment (in line with how the students in Bøe et al.'s (2018) study most easily adapted to aspects of the innovative approach that resembled traditional physics classrooms).

In the figured world of university physics teaching, there is, thus, a power relation created between traditional and reformed means of teaching, where the latter is elevated with references to physics education research and popular cognitive psychology. This communicates to the student teachers in the cohort that teaching and learning approaches ought to be based in research. The focus in the reformed classroom is also shifted from the quantity of teaching (in terms of numbers of concepts covered and problems solved) to the quality of teaching (covering a few important concepts in depth and gearing the problem-solving towards a combination of mathematical manipulation and conceptual understanding). However, this shift from quantity to quality is not a consistent one; in accordance with previous studies (Hasse 2002; Carlone 2004), we can also in this classroom identify contradictory messages about 'the good physics students'. Outside of the classroom, in the students' independent study, it is the number of hours put into practicing quantum mechanics that is foregrounded.

The university teachers do in some situations try to counteract the taken-for-granted story of physics as providing right or wrong answers, by, for example, formulating clicker questions where several responses can be correct and also by repeatedly pointing out that there may be more than one correct answer to these questions. Still, that physics questions/problems often only have one correct answer makes student participation in classroom discussion potentially risky; by answering incorrectly, your position as physics insider is threatened (Berge et al. 2019). That the students even after having just answered a question using the clickers still are reluctant to discussing their answers in public strengthens the impression that delivering potentially incorrect answers is perceived as risky. The use of clickers, as an anonymised way of answering, can also be understood as a way of pedagogically handling this risk.

In an anthropological study of an undergraduate physics programme, Hasse (2002) found that while students were explicitly encouraged to follow instructions for laboratory exercises, it was students who deviated from the assignments who were seen as creative and as such potential future research physicists by the university teachers. Hence, in her study, there were contradictory messages regarding the 'good physics student' versus the 'future research physicist'. In relation to this, it is interesting to notice how in the classroom we have analysed the group work activity is construed as common to the figured world of physics teaching and learning and the figured world of professional physicists. Collaboration is presented as beneficial to learning, but also as an important skill for the professional physicist. Thus, the students are motivated to participate in a learning activity by its value for their future profession. As such, 'the good physics student' and 'the potential physics researcher' are not, in the context of group work, construed as different, but rather conflated into an idea of a socially skilled physicist. The students are thus given the opportunity to simultaneously identify as the good student and the future research scientist.

Consequences for Physics Teacher Education

Physics teacher education typically consists of a combination of physics content courses, pedagogical courses and school placements; the observed quantum mechanics course is a mandatory part of the high school physics teacher education programme. Thus, what is communicated about the teaching and learning of physics in the course is highly relevant for these teacher trainees, even if physics teaching methods are not an explicit part of the course content. Previous research has noted that physics teacher education is often fragmented, given that the content courses are taught by physics departments and the pedagogical courses by departments of education, something that is considered problematic (Larsson et al. 2018). A factor that has been suggested as important for high-quality physics teacher education is the collaboration between physics departments and education departments (Sandifer and Brewe 2015, p. 3).

The first thing that is noticeable when looking at the course in the context of its place in a teacher education programme is that the assumed future of the students is something that is repeatedly alluded to. For example, we have seen that the use of group work is motivated in part by its usefulness for research physicists. However, these assumed futures are always those of physicists engaged in research and/or development, in academia or industry. In a sense, the student teachers and their futures are invisibilised, yet the teaching and learning of physics is frequently foregrounded.

The inclusion of an explicit treatment of physics teaching and learning in a physics content course during the teacher education has a potential to mitigate the fragmentation that physics teacher educations often has been criticized for (Larsson et al. 2018). However, in doing so, it is important to coordinate how theories of learning are treated within the different parts of the physics teacher education, both in terms of which theories are introduced and in terms of their ontological status (e.g. whether a theory of learning is presented as a fact or as one of several interpretational models). For example, the individualised cognitive view presented during the observed quantum mechanics course could be explicitly discussed in relation to the socio-cultural perspective emphasised in the Swedish curriculum (e.g. the Swedish department of education 1997) and, as such, serve as a complement to this perspective.

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