Examining Power, Knowledge and Power Relations in a Science Research Apprenticeship

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Abstract

The science laboratory is a politically-entrenched space where complex power relations interplay while social agents learn about the rules and routines to ensure safety, precision, and reproducibility in research work. This paper presents a case study of two Singaporean students undergoing apprenticeship in a three-year school-based School Scientist Programme. They engaged in an open and authentic science inquiry involving chemical synthesis in the school's science laboratory under the apprenticeship of an in-house School Scientist who started the programme. The goals of this paper are to offer an alternative—critical and nuanced—lens to the dominant positivist and social constructivist discourse about science research apprenticeship. Using visual ethnography approach, we collected videos and photographs of the students' and School Scientist's interactions during the science research over the first 18 months of the programme. The study documented critical events that showed shifts in control over knowledge construction and mastery of the chemical synthesis craft as the science research progressed. This paper contributes to the Foucauldian theory of power in offering an alternative view to the dialectical explanation of power and knowledge. First, it shows that while there is an overall gain in knowledge of chemical synthesis increased during the apprenticeship, the power relationship fluctuates when a different genre of chemical synthesis work was introduced. The fluctuation is related to the overtaking and relinquishing of control (power) with the latter leading to the construction of knowledge. Second, we show how the power relationship, involving the interplay of power and knowledge between the expert and apprentice, is more interconnected and complex. The findings of this study have implications for teachers who want to plan and enact authentic science inquiry with their students.

Keywords: apprenticeship, power, power relationships, chemical synthesis, science laboratory

A School-Based Science Apprenticeship

Before schools became the main institutions for learning, the most common means for the transmission of skills and knowledge came through participation in apprenticeship experiences. Apprenticeship in science education is the typical approach to enculturate students into the norms and practices of doing science. In the context of chemical synthesis, learning about chemical reactions in theory is vastly different from learning the actual process of synthesizing and characterizing chemical compounds. Theoretical discussions about chemical synthesis involve knowledge about the chemical properties of reagents, reaction conditions, and mechanisms undergirded by chemistry concepts. Characterization of chemical compounds entails knowledge about analytical measurements and interpretations of data. Laboratory processes require attention to details related to safety, precision, and reproducibility. Apprenticeship is the typical model or approach in which the apprentices in chemical synthesis laboratories develop into experts. The process of gaining apprenticeship, however, is not straightforward as the apprentice and expert will constantly exercise power to negotiate control over imparting knowledge and constructing knowledge. Therefore, we see that apprenticeship, in the context of a chemical synthesis laboratory, is politically entrenched because the interactions involve asking questions such as “Who owns the knowledge and control over the process at various stages of the apprenticeship?" The answer to this question will provide insights into better ways of managing the expectations of the expert and apprentice, especially in learning contexts that are less teacher-centric and more student-centric (e.g., authentic science inquiry lessons), so that tensions over control and ownership of power and knowledge may be mediated. In this paper, we offer a critical examination of power relationship between the apprentice and expert to illuminate ways in managing the fluidity and complexity of apprenticeship for better learning outcomes. By "critical", we refer to questioning what is often taken-for-granted to be the norm. In this case, the norm of the apprenticeship is that: (a) the expert will take the lead and the apprentice will follow the lead to gain mastery, and (b) the process involves transfer and uptake of knowledge and skills. As a counter-narrative to both points, we show: (a) the blurring of the expert and apprentice divide, especially when the work to be completed is novel to both groups; and (b) that beyond the façade of transfer of knowledge and skills in apprenticeship, are the complex transactions of power and knowledge.

This paper reports on an inaugural programme, the School Scientist Programme (SSP), at a Singapore school for Grades 7-12 students. A School Scientist (second author) initiated SSP to provide authentic research experiences for highly-abled students interested in science research. By authentic, he meant having students experience science research like real scientists. Drawing on his expertise and experience as a synthetic chemist, he worked with the students to design an experiment involving the synthesis and characterisation of novel osmium organometallic compounds which have potential anti-cancer activity. While the School Scientist had the experience of working with adult learners such as graduate students in the university chemistry laboratory, mentoring students in SSP was different as they were younger learners with limited or no experience doing authentic scientific inquiry and knowledge about chemical synthesis. While the SSP could position himself as the expert with all the knowledge about chemical synthesis and tell his apprentices what to do or demonstrate how things are done, he undertook a different approach that required his young apprentices to infer and apply their knowledge and skills after some basic training. The goal of this paper is to provide a critical examination of the *power relationship* between the expert and apprentice in a chemical synthesis laboratory context where the apprentices are high school students.

In the next section, we provide a discussion on the literature on apprenticeship followed by power relationships—a critical lens to examining the process of apprenticeship.

Apprenticeship

During apprenticeship, the apprentices engage in legitimate peripheral participation in a community of practice, resulting in the situated learning of skills and knowledge required to become an expert in the field (Lave and Wenger 1991). The activity becomes essential for a novice to be enculturated into the community, and for the community to transmit their practices. While the apprenticeship models of learning may occur in a wide variety of contexts. One key characteristic of apprenticeships is the indistinguishable nature of learning and the practice of work. The prime motivation for learning stems from engaging in authentic activities which propels the newcomer towards becoming an expert practitioner central to the community. This contrasts with formal instructional settings such as classrooms in schools where students learn skills and knowledge as abstract, decontextualized formal concepts, independent of the situation in which they are used. Within the community, the expert helps shape the learning trajectory for the novice by partitioning the tasks into appropriate chunks for the apprentice, shaping their identities and providing structure as well as meaning to knowledgeable skill. In return, the apprentice through mutual engagement with as well as direction as support from the expert, demonstrates learning by accomplishing the tasks in ways that are analogous to that of the expert, moving from the periphery towards full membership in the community.

In a manner like traditional apprenticeship, cognitive apprenticeship methods attempt to enculturate students into authentic practices through activity and social interaction (Brown, Collins and Duguid 1989). While the emphasis of craft apprenticeship is on the transmittance of physical skills and processes from the master to the apprentice, the focus of the learning-through-guided-experience for cognitive apprenticeship is on cognition and metacognition, and is targeted fundamentally at inculcating the processes that experts use to handle complex tasks. In craft apprenticeship, market forces dictate the type of products and hence the tasks that the apprentice must fulfil to meet these needs; for the master, teaching the skills in the context of their use is thus emphasized. On the other hand, cognitive apprenticeship recognizes that students learn how to apply their skills in different contexts; the tasks and problems are hence, chosen to allow the students to practice techniques or methods in diverse settings and increasing complexity.

In its acknowledgement that the goal of education is to provide usable and robust knowledge, cognitive apprenticeship supports learning by enabling the students to acquire, develop, appreciate and actively use conceptual tools in authentic domain settings. To do so, expert teachers have been found to adopt the methods of modelling, coaching, scaffolding, articulation, reflection and exploration (Collins, Brown and Newman 1989). In *modelling*, the students observe as the teacher performs a task and from there construct a conceptual model of the processes required to accomplish it successfully. *Coaching* involves the teacher monitoring students as the latter execute the task, providing guidance and feedback for the students to attain competency in their performance. As the students strive towards expert performance, the teacher employs *scaffolding* by giving them support and accurate assessment of their proficiency levels; the teacher gradually decreases the level and amount of support given in a process termed *fading* as the students' become more capable. The purpose of *articulation* is to encourage the students to express their thought processes explicitly and accurately, while for *reflection* the students compare their thinking processes against those of the experts and other students. Finally, for *exploration* the students take on new challenges and problems, attempting to solve them with the acquired knowledge and conceptual tools.

In science research apprenticeships, learning opportunities are created as science is practised, and involves students partnering with scientists to conduct scientific investigations (Burgin, Sadler and Koroly 2012). The apprentice learns and works "at the elbows" of scientists at a professional science setting (Barab and Hay 2008), seeking unknown solutions to real-life problems of value to the scientific community and hence may be regarded as highly authentic (Burgin and Sadler 2013). These experiences typically occur in university science or engineering research laboratories where the learner is mentored by a faculty member or their graduate students (Bleicher, 1996), in programs lasting from two weeks (Hay and Barab 2001) to two months (Bell, Blair, Crawford and Lederman 2003).

A recent review of the literature regarding empirical studies of research apprenticeship programmes (Sadler, Burgin, McKinney and Ponjuan 2010) highlighted several positive outcomes experienced by the participants including an enhanced understanding of the Nature of Science (NOS) (Charney, Hmelo-Silver, Sofer, Neigeborn, Coletta, and Nemeroff 2007), promoting career aspirations in science (Stake and Mares 2001), increased scientific content knowledge (Grindstaff and Richmond 2008) as well as skills (Seymour, Hunter, Laursen and Deantoni 2004) amongst other reported promising impacts.

The review of the literature illuminates a gap in the critical analysis about apprenticeship. Specifically, it lacks a critical discussion on the power dynamics that occurs during the development of the apprenticeship to bring about change in the students' learning. Alessia Contu and Hugh Willmott (2003) have purported the revitalisation of the situated learning theory—from which the discussion of apprenticeship is rooted—to be understood in terms of the learning practices being enabled and constrained by their embeddedness in relations of power. According to them, Jean Lave and Etienne Wenger's work aspired to incorporate considerations of power in respect to the social organisation of and control over resources, or are outcomes of communities of practice. In this view, power can impede or foster access to and continuing membership of communities engaging in legitimate peripheral participation. In this light, apprenticeship is thus a power-invested process of bestowing legitimacy upon apprentices such that they become an identified member of the scientific community. Power relations can mediate the acquisition, maintenance, and the transformation of meanings in the apprenticeship process, including what is deemed as "legitimate".

Power Relationships

Michael Foucault's (1977) discussion of institutional power in *Discipline and Punish: The Birth of the Prison* offers valuable and critical lens to analyse how power is exercised in prisons, hospitals, military, and even schools with the aim to discipline or "train". The Foucauldian theory of power may be summarized into three main points. First, power does not work through obligations or prohibitions but is invested in people, transmitted by them, and through them. In other words, power works through self-surveillance as people discipline, regulate, or control their own behaviours. Two points may be distilled from this point and applied to the context of the SSP apprenticeship. First and as mentioned earlier, the two students in this study had made the choice to undertake SSP despite it being a new programme. The students had explained that they wanted to learn how authentic science research was carried out and hence, they invested their time and energy in their SSP project. Second, they were aware that unlike typical science lessons, they had to monitor their own work progress and work in the laboratory even if the School Scientist was not around to closely monitor every step of the synthesis work. As such, the apprentices were not always subjected to direct close monitoring as opposed to self-monitoring of behaviours and work progress.

Second, power is polymorphous, delocalized and has temporal relations since there can be no power relations without the generation of constitutive field of knowledge which is determined from the process of struggle and extension over the resistance to power. This implies that the control of knowledge reproduction can be fluidly transacted between the expert and apprentices and that no single individual is always in possession of the knowledge being constructed. In the context of SSP, power in the form of teacher control was stronger at the start of the programme as the students had little knowledge about the ways to handle the apparatus and equipment, and the chemistry principles beyond the design of the instruments. As the students gradually gained expertise, the teacher control was reduced and they took over the control of the outcomes of the synthesis work.

Third, the school building is a "pedagogical machine" (Foucault 1977, p. 172) serving as a mechanism for training. The layout, furniture, and apparatuses of science laboratories such as allows for specific activities to be carried out safely and with reproducibility. The open benches allow for surveillance for the checking for obedience and work. The transparent fume cupboards allow for monitoring of activities in the cupboard by others. Again, in the context of SSP, the school was equipped with basic facilities to carry out scientific research. The science laboratory in which the students carried out their synthesis work, could be the "pedagogical machine" in which students learnt the normative practices of chemical synthesis work. They learnt how to handle the apparatus and instruments "properly" according to how they were designed so as to obtain precise and reproducible results.

Implicit in the Foucauldian theory is the dialectical relationship between power and knowledge. Specifically, power enables and circumscribes knowledge; similarly, knowledge enables and circumscribes power. Conceived using this Foucauldian idea, relations within a social body embodies the dialectical interplay of power and knowledge. In the context of apprenticeship, this could mean that experts control the (re)production of scientific knowledge in the enculturation of apprentices; empowered with the scientific knowledge, the apprenticeships could perform the scientific craft with greater understanding, precision, and caution. In this view, relationships embody power and knowledge, and having power entails knowledge and *vice versa*.

While the dialectical view explains the close-knitted relationship between power and knowledge, it does not explain the complexity of the apprenticeship process which we see is politically-entrenched as it entailed a careful management of relationships between the expert and apprentices. Through an analysis of the shifts in control over knowledge (re)production over 18-months in a synthesis chemistry research project supervised by a School Scientist and two high school students, this paper aims to fill the gap in the apprenticeship literature by examining the power relationships of the expert and apprentices as the latter learn to synthesize a novel organometallic product. Additionally, this paper will contribute to the chemistry education literature that is currently lacking in studies with a critical lens and studies conducted in Asian contexts (Teo, Goh & Yeo 2014). Specifically, the research question we want to address is: *How* *does the power relationship interplay between the School Scientist (expert) and students (apprentices) during the synthetic chemistry research project?* Power relations may be studied by understanding the discourses used by individuals and groups. As Flis Henwood (1998) argued, "subjectivities are understood as constituted through a complex interconnection of discourses, which have been defined as the interrelationship of themes, statements, forms of knowledge and positions held by individual in relation to these" (p. 39). The positioning, or "the assignment of fluid 'parts' or 'roles' to speakers in the discursive construction of personal stories that make a person's actions intelligible and relatively determine social acts" (van Langenhove and Harré 1999, p. 17), alludes to the power relations between the various actors. In our work, we examine verbal and non-verbal discourses. To address the research question, we examine who is in control of the knowledge (re)production during the various parts of the apprenticeship process, how the control and knowledge changes during and after the entire apprenticeship process.

Research Details

School Scientist Programme

To offer additional advantages and address some of the challenges posed by the current research apprenticeship programs for high school students, a School Scientist at an elite high school in Singapore, initiated the School Scientist Program (SSP). SSP is a pull-out programme for students interested and competent in science to engage in an authentic science research project. In addition to the SSP, students from the school have the option to choose from more than ten other project genres such as service learning, art and the humanities. Students were recruited into the SSP when they were in Grades 9 or 10, and would engage in a two to three year-long authentic open-ended research project under the apprenticeship of a School Scientist. The extended apprenticeship period served to enable the students to focus on the learning process and foundation building in the earlier years for the students to eventually gain a deep understanding of how science research was carried out. As the initial phase (first and second year) of the programme was situated in the school, SSP was envisioned to give rise to closer and more frequent interaction between the apprentice and expert over a sustained period, as well as leverage on the important role played by peer collaboration and support in the student learning of science content and science research skills. Building on explicit and purposeful instruction by the School Scientist, the students continually reflect and underwent formative and summative assessment to track their progress. After having acquired an understanding of the nature of science and scientific inquiry, as well as gain proficiency in the basic laboratory technical skills and related scientific content knowledge during the foundational years, the students would be well-poised to engage in higher cognitive skills such as formulating their own research questions and designs, and continue their research apprenticeship in a laboratory at a university or research institute. The duration and nature of the SSP would enable the students' intellectual and affective growth to be continuously captured and provide a well-documented account of the quality of learning by the students as they develop within the programme.

In the inaugural year of implementation of SSP, only two students signed up to participate in the programme. While the entire duration of the SSP lasted three years for these two students, most of the laboratory work was completed during the months of June and December when the students had their school holidays. This paper discusses the beginning part of the students' participation in the SSP. Figure 1 below shows the key activities during the first 18-months of the three-year programme.

<insert Figure 1 about here>

The Expert and Apprentices

Kenneth held the designation of a School Scientist at the school; he was involved in mentoring high ability students in science research and conducting workshops on science communication for students. Prior to this designation, he taught chemistry to senior high school (Grades 11-12) students and had more than ten years of classroom experience teaching chemistry. He has a doctorate degree in chemistry and is proficient in organic and organometallic synthetic chemistry. Whilst teaching in school, he continued to pursue his passion in research by taking sabbaticals to work with various chemistry researchers in universities around the world.

Ziwei (pseudonym) was a Grade 10 male student at the school. He participated in SSP as he wanted to "get a closer feel to real world scientific research" (Ziwei, interview, December 10, 2013). He explained that he did not want to participate in science research programs that emphasized on only achieving results because he valued the importance of the process of learning. In his understanding, some science research would take many years to complete. He hoped that his learning experience in SSP would prepare him to embark on a career related to chemistry in the future.

Sau Yong (pseudonym) was a Grade 9 male student at the school. He participated in SSP as he wanted to have more hands-on experience learning science in the laboratory. Since the SSP was longer in duration that the other programs offered by the school, Sau Yong felt he would have more hands-on experience working in the laboratory. Similar to Ziwei, he liked the idea that SSP valued the learning process and not results alone (Sau Yong, interview, December 10, 2013). He believed that the authentic experience, such as being able to troubleshoot and solve problems during the research, would better prepare him well for his future career as a scientist.

Video Data

The data analyzed for this paper were drawn from a larger data set consisting of video-recordings of the research work, audio interviews with the apprentices, and photographs of the apprentices' written artefacts. In this paper, we focused only on the videos that captured the process of the chemistry research work. The duration of each laboratory session varied and could last between one to three hours. During data collection, the video camera was mounted on a tripod and placed near the students' laboratory bench or fume cupboard where they performed the experiments, or table where the expert and apprentices discussed the research plan and direction.

Event-Oriented Inquiry

A total of 11 laboratory sessions were videoed. For the purpose of this paper, we only selected those that were captured in the first six months for discussion. We have two reasons for this decision. First, there were more interactions between the School Scientist and apprentices during the first six months when the latter were learning the basic skills required to carry out chemical synthesis work. The apprentices carried out the tasks more independently after the first six months of training. Hence, the videos captured in the first six months contained richer data for us to distil the inter-actions and hence, the apprenticeship model. Second, similar skill sets were applied in the synthesis and characterization of the osmium precursor and the target organometallic compounds from the seventh month onwards. Hence, there were some repetitions of the events in the latter videos.

We adopted event-oriented inquiry in the selection of relevant video data for analysis. According to Kenneth Tobin, Stephen Ritchie, Jennifer Oakley, Victoria Mergard, and Peter

Hudson (2013), an event is alike "a spike in the curve" or a salient contradiction that changes the nature of what is happening. In our work, an event is not a contradiction but an illuminating occurrence that suggests, in implicit or explicit ways, the interplay of power relationships between the experts and apprentices during the science apprenticeship. As mentioned in the literature review, experts adopt practices such as modelling, coaching, scaffolding, articulation, reflection, and exploration in their work. In our coding of the videos, we look for episodes of such practices during apprenticeship. Based upon the coding, we found most of these practices being enacted in three events, namely, expert demonstration, apprentice practice, and apprentice exploration. These events are also typical of apprenticeship models where the expert first show the normative practices of the field, followed by hands-on experience by the apprentices, and finally, independent exploration by the apprentices to demonstrate competencies.

Events have temporal and contingent qualities that do not always allow for a seamless narrative (Ritchie and Newlands 2016). Following the coding and identification of three main episodes, we wrote three narratives describing separate events in chronological order for the purpose of showing the progression of apprenticeship.

Progression of Apprenticeship

In this section, the findings were presented in the form of narratives. A total of three events were described to illuminate the power relationships during the apprenticeship. In the beginning, there were many new and unfamiliar pieces of apparatus, the relevant skills required to utilize them, as well as the related scientific concepts for the apprentices to grasp. Kenneth closely supervised these initial sessions and modelled for both Ziwei and Sau Yong, introducing them to the apparatus, coaching them on the proper techniques to use the apparatus and helping them develop the conceptual understanding behind the design of the apparatus as well as the laboratory techniques. The students were given opportunities over several sessions to practice the techniques that Kenneth had demonstrated to them. Due to their inexperience, the apprentices initially floundered with some of the tasks. Displaying perseverance, the apprentices practiced and worked on improving their competence in the techniques, which was coupled with an acceleration of the understanding of the relevant concepts underlying the hands-on skills. In essence, the macro descriptions illuminate the skills transferred but at the micro-level, the non-linear processes during which power was interplayed, were revealed.

Event 1: Imbalanced power relationship in expert demonstration

Table 1 below shows an excerpt of the transcript of the first laboratory session for the apprentices' hands-on experience. In this session, the expert demonstrated the proper handling and manipulation of equipment (e.g., weighing balance) and apparatus (e.g., micropipette). These are some of the skill sets the students acquired in the first six months of SSP. Thereafter, the apprentices applied the same skill sets to synthesise the novel organometallic compounds. The excerpt below shows the dominance of the expert verbal and non-verbal discourse during the demonstration to acculturate the apprentices so that they learn about the correct way of handling the micropipette to ensure accuracy in measurement.

<Insert Table 1 about here>

Kenneth initially allowed the apprentices to get a feel of handling the micropipette by giving each of them a micropipette (with the tip already inserted), and two beakers—one empty and one half-filled with water to replace the actual reagents that they would be using later. Kenneth observed that while Ziwei could hold the micropipette correctly by wrapping his palm around the top of the micropipette and placing his thumb on the plunger, Ziwei tried to draw the water in the beaker by dipping the tip of the micropipette into the beaker followed by pressing the plunger. Kenneth then stopped the apprentices and repeated Ziwei's actions, highlighting the incorrect sequence of actions. He pointed out the mistake Ziwei made and explained to the apprentices that by doing so, there would be a likelihood of air bubbles being introduced to the pipette tip, resulting in an incorrect volume of liquid being drawn up. Kenneth then proceeded to explain to the apprentices that the micropipette plunger could be controlled via two stops and further elaborated on the use of each of the stops in the pipetting process. He demonstrated to the apprentices the proper technique of pressing the plunger down to the first stop before immersing the plunger into the liquid, followed by releasing the plunger slowly to ensure the continuous intake of the correct volume of liquid into the tip.

In this event on demonstration for the enculturation of the scientific practice, there was greater expert control and imparting of knowledge and skill from the expert to apprentice. When Kenneth asked the apprentices to describe what they thought happened when the plunger of the micropipette was pressed down, Ziwei could relate to his previous experience with using the single volume glass pipette in his chemistry practical lessons. He replied that by doing so, a volume of air would be pushed out of the micropipette. However, Ziwei revealed his misconception when he pressed to expel the air only when the tip was immersed into the solution. To address Ziwei's mistake, Kenneth intentionally mirrored Ziwei's actions with the micropipette by placing the tip into the beaker of water before pressing the plunger down and releasing it quickly again. In doing so, the micropipette sucked in some of the air that it had previously expelled in the process of sucking up the solution. By deliberately pausing and asking the apprentices to observe the air bubble in the pipette tip, he helped them to visualise the consequence of the mistake. Kenneth also perceived that the apprentices did not realize the micropipette was built with two stops, each serving a specific purpose, as he observed that Ziwei pushed the plunger all the way down to the second stop before taking in the solution. Kenneth followed up with the apprentices by showing the correct method for using the micropipette. At the same time, he externalized the thought processes by explaining to the apprentices the purpose of each of the two stops of the plunger. As a result, the apprentices could observe the processes required to perform the task proficiently, better comprehend the skill to complete the task and form a procedural understanding.

Event 2: Relinquishing more control to the apprentices with experience

The next event pertains to the use of the electronic weighing balance to weigh out a required mass of solid starting material by the apprentices. In contrast to the micropipette which both apprentices had not encountered before embarking on SSP, Ziwei had former experience in using an electronic weighing balance in his chemistry practical lessons. Hence, instead of modelling the sequence of actions for the students, Kenneth requested for Ziwei to demonstrate what he knew. Table 2 below shows an excerpt of the transcript of this episode.

<Insert Table 2 about here>

After Ziwei placed the weighing bottle on the electronic weighing balance, Kenneth asked him to pause his actions and asked Ziwei to explain why he first obtained the mass of the empty weighing bottle. Ziwei replied that he did this step to utilize the "TARE" function found on the electronic weighing balance. Kenneth acknowledged Ziwei's explanation and highlighted this as a learning point for Sau Yong. When Ziwei was unable to correctly name the function ("TARE"), calling it "the zero setting", Kenneth introduced both students to the name of the "TARE" function as well as the two ways in which the students could obtain the mass of the solid to be weighed out (with and without using the "TARE" function). Ziwei then further elaborated that by pressing the "TARE" function when the asterisk sign appeared on the reading panel, indicating that the reading was stable, the reading was reset to zero.

In this session, Kenneth leveraged on Ziwei's familiarity with the manipulation skills required to operate the instrument and utilised a different apprenticeship approach. The session was designed to probe Ziwei's prior knowledge as well as reinforce the procedural and conceptual knowledge underlying the operative skills for using the electronic weighing balance for the apprentices. In this case, the more experienced Ziwei played the role of a demonstrator to Sau Yong, who had not used the instrument before. Kenneth played the role of an expert to both apprentices. Kenneth interjected Ziwei's actions with a probing question on why Ziwei measured the mass of the empty weighing bottle initially, providing a mental trigger to stimulate Ziwei's thinking. Ziwei could apply his prior knowledge and articulated his thought processes successfully to answer Kenneth's query. By acknowledging Ziwei's correct thinking, Kenneth validated Ziwei's understanding of the use of the equipment. Kenneth then went on to build on Ziwei's response by reminding both students of the use of the "TARE" function. In this event, Ziwei took greater control over the enactment of knowledge with the expert who legitimized his knowledge through questioning and expert acknowledgement.

Event 3: Shift in control to apprentices for exploration

Figure 2 below shows pictures extracted from three sessions where the apprentices performed tasks with the expert by their side observing them and providing in-time advice. In Figure 2(a), Kenneth reminded Sau Yong to use a clean spatula to push down the edges of the filter paper in the Büchner funnel of a suction filtration setup to ensure efficient separation. In Figure 2(b), Sau Yong measured the melting point of a solid using the melting point apparatus. Kenneth stood beside him, ready to provide feedback and suggestions on his performance. In Figure 2(c), Kenneth observed and conducted a diagnosis of the students' skill proficiency level as they measured out a predetermined volume of liquid, and transferred the liquid from a bottle to a measuring cylinder using glass droppers.

<Insert Figure 2 about here>

As the scientific research progressed and the apprentices acquired diverse scientific craft and enacted them with greater proficiency. Kenneth's role gradually transitioned from that of a demonstrator and coach to an observer. While Kenneth had to initially point out the errors that the apprentices were making during their work, the apprentices' proficiency gradually developed to a stage where they were able to identify the sources of errors in their techniques and self-corrected their own mistakes. Accordingly, Kenneth gradually removed his scaffolding support until the apprentices were capable of performing the tasks without supervision.

After the apprentices had acquired expertise on the laboratory techniques and procedures, as well as the relevant content knowledge on stoichiometric calculations, they utilized their knowledge and skills to carry out the synthesis of the chemical compound required for their project. By this time, both students were already skilled in the requisite laboratory protocols. As a result, they assumed responsibility and took control of their project. There was no need for Kenneth to constantly keep a close watch on the apprentices and they carried out their synthesis almost independently. Several examples of this are shown in Figure 3. In Figure 3(a), Sau Yong measured out the required mass of a solid starting material using the electronic weighing balance. In Figure 3(b) Ziwei set up the reaction in the fume cupboard and transferred the required volume of solvent into the reaction vessel, and in Figure 3(c) he filtered out the solid product using suction filtration.

<Insert Figure 3 about here>

Apprenticeship and Power Relationships: Discussion

The three narratives illuminated the changes in power relationships with shifts in control to ensure that: (1) canonical knowledge about chemical synthesis practices were transferred with understanding from the expert to apprentices, and (2) the apprentices gained expertise and understanding through actively co-constructing knowledge and practising the craft so that they internalized the concepts and procedures. In this case, power—as enabled by having the expert knowledge and the specialized craft of chemical synthesis work—was delocalized as it was being imparted by the expert to the apprentices. The delocalization happened through the use of non-cultural and cultural tools, cultural space, and cultural knowledge.

An example of the non-cultural tool was the "gaze". Kenneth was watching the apprentices perform the craft and his gaze provided the surveillance which was used to monitor the apprentices, who would inevitably feel that they were being watched closely and hence, performed the craft with care to obtain approval. Without the approval of the expert, the apprentices would not be able to continue with the chemical synthesis work. The cultural tools were the sophisticated science apparatus and equipment that only experts such as Kenneth knew the appropriate methods and procedures to handle them properly. The cultural space refers to the laboratory, the laboratory bench, and fume cupboard which represented the "pedagogical machines" which were the legitimate space where chemical synthesis experiments were carried out to ensure safety. The cultural knowledge refers to the theoretical concepts underpinning the experimental design, and proper use of apparatus and equipment to ensure that the results can be reproduced by someone else when the experiment is repeated. In sum, the purpose of delocalising power ensured that the cultural and canonical knowledge of synthesis chemistry was passed on so that accuracy, safety, and reproducibility of scientific results were retained.

An interesting learning point can be drawn from this study. Critical studies in science education have advocated for balanced power relationships between the teacher and students in the science classrooms (see e.g., Puvirajah, Verma, and Webb 2012). This study shows teaching and learning in the form of an apprenticeship model involved dynamism in the negotiations of power relationships during the apprenticeship process. There was a gradual release of control by the expert in the process of having the apprentice gain experience with handling the apparatus and equipment. However, this control was regained when the apprentices faltered or when a new activity had to be introduced. An important implication of this is that apprenticeship, in the context of chemical synthesis research work, demands the dynamic management of power relationships alike walking on a tight rope (Teo 2013). In other words, it is not about ensuring a balanced control throughout the apprenticeship. Rather, it involves the expert constantly making decisions on when to release control, when to take over, and when to keep a close eye on the apprentices' work using various tools. In this case, the divide between the knowledge that was imparted or constructed becomes blurred. Ironically, it is also through such an unclearly defined process that apprentices gradually become legitimized as members of the synthetic chemistry community.

In connection to the non-linear power relationship observed during apprenticeship, we observed a different kind relationship between power and knowledge in the apprenticeship process that was different from the dialectical model reported in the literature (Gaventa and Cornwall 2007). Specifically, there was an overall gain in chemical synthesis knowledge from the beginning to end of the reported 18-month apprenticeship. However, this apprenticeship process can be segmented into different genres of activity depending on the types of equipment or apparatus used. For example, performing pre-laboratory calculations, weighing the mass of a substance and filtration of a suspension. Each time a different genre of activity was introduced, the expert power control was high; this control, however, would gradually shift to the apprentices over time as they gain expert knowledge. Figure 4 offers a diagrammatic view of the shifts in expert control with the change in the genre of the chemical synthesis activity. While there was an overall gain in chemical synthesis knowledge, the power control typically began with high expert control and gradually shifted to higher apprentice control as they took charge of the research work. Genre 1-3 represents the different types of chemical synthesis activities such as suction filtration, melting point determination, weighing of substances and so on. We refer to them as "genres" as each activity requires a different set of skills, equipment, apparatus, and/or chemistry understanding. We acknowledge that this change need not be linear and could fluctuate within each genre of activity. The extent of shifts in control can differ as it transits to the next genre.

<Insert Figure 4 about here>

Concluding Remarks and Implications

In this study, we provide a critical analysis of power, knowledge, and power relationship between a chemistry expert and two apprentices in a chemical synthesis project. We show that as the genre of chemical synthesis work changes, power, in the form of control of knowledge (re)production, shifts accordingly. The micro-changes within each genre of work contrast with the overall increase in knowledge about synthesis chemistry. This finding contrasts with the dialectical view of power and knowledge and henceforth, contributes to the literature rooted in Foucauldian theory of power and knowledge, and apprenticeship. In this concluding section, we offer an alternative representation of the power relationship between the expert and apprentice in the apprenticeship model as shown in Figure 5.

<insert Figure 5 about here>

To reiterate an earlier point, apprenticeship is a power-invested process that bestows legitimacy of their membership in the scientific community. In Figure 5, we show that the expert exercises power in the form of control over what knowledge to impart and how to impart it. We have shown how the expert (teacher) imparted his knowledge about chemical synthesis through modelling, coaching, scaffolding, articulating, reflection, and exploration practices so that his apprentices (students) acquire the canonical knowledge to perform the tasks in ways that are typically adopted by other synthetic chemists. The apprentices were given opportunities to demonstrate what they were able to do (power) and evidence of their knowledge were judged by the expert who then decided on the next course of action.

On the above note, we want to return to the earlier points of power to explain how the entire apprenticeship process was dynamic and self-sustainable. First, the expert did not exercise the control over students to make the learning process obligatory. Rather, the apprentices chose the programme and subsequently were empowered by the new knowledge gained. In order words, power was transmitted in the form of knowledge and power was invested in the apprentices. Second, Figure 5 shows the polymorphous nature of power relationships shaped by the continual flow of power and knowledge from the expert to apprentice and vice versa. Third, SSP can be said to be the "pedagogical machine" (Foucault, 1977, p. 172) or platform for the apprenticeship to happen.

The findings have informed Kenneth on the way to enact the apprenticeship model in his supervision of new students, which attained a steady growth in number, in subsequent years of the SSP. More importantly, this study has broader implications for teachers who want to guide students to do authentic (open) science inquiry. Using a case study of a biology teacher, Barbara Crawford (2000) mapped out ten roles that science teachers play in science inquiry. The roles of the teacher include being the motivator, diagnostician, guide, innovator, experimenter, researcher, modeller, mentor, collaborator, and learner. She also reported that teachers have the highest level of involvement in inquiry-based lessons. We infer from Crawford's study that the teacher is positioned as the expert who plays a significant role in shaping the science inquiry experience for students. In our paper, we have taken the discussion further, by unpacking the power relationships embedded in the role of the teacher as the expert and offering an apprenticeship model that teachers may find useful in navigating their roles in authentic science inquiry *with* their students positioned as apprentices.

As a final note, we argue that in understanding how power and knowledge shapes the power relationships of the expert and apprentice, a more balanced teacher- and student-centric approach to science inquiry may be enacted.

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