CRITICAL THINKING IN CHEMISTRY EDUCATION: A STUDY FOR PRACTICAL APPLICATION IN SECONDARY EDUCATION BASED ON QUESTIONS, EXPLANATIONS, AND ARGUMENTS

by

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Abstract

This study attempts to insert critical thinking practices in the secondary chemistry classroom, specifically Years 9 and 10. Critical thinking is a concept elusive in nature, with several definitions, addressing both the disposition and the skills of an aspiring critical thinker. Through the theoretical exploration of CT, practical benefits emerge for acquiring CT within the scope of chemistry via the use of questions, explanations and arguments. The challenge of the study has been to conceptualise and implement CT in teaching and learning practices. Two Year 9 groups and one Year 10 group with their teachers participated in the study, each enriching the data with different approaches to critical thinking. Trends of teaching practices emerged within and across the groups of participants and influenced the learning practices of the students. As a definition for critical-thinking-as-praxis developed with the aim to provide applicable guidance to education practitioners for enhancing critical thinking in their practice. Resembling a loop of stages for the development of critical thinking for the learners and actions at each stage of development for the teachers. According to the analysis of the data, teacher attitudes had a direct impact on student attitudes and the success of using the praxis was based on frequent practice towards CT development.

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INTRODUCTION

The aim of this research is to examine whether practices that enhance critical thinking can be applied in a mid-secondary chemistry classroom setting. Critical thinking (CT) is considered a marker of good quality education; and well-structured thinking abilities. In professional development, CT is considered a necessary component for scientific thinking and inquiry for the novice and professional scientist.

Education policies have included critical thinking as a goal from the early 20th century; influenced by the teachings and philosophy of John Dewey. Dewey (1933) introduced the term ‘reflective thinker’; with the objective that learners develop their thinking skills using their personal experiences, observations and knowledge. The term critical thinking (CT), extending Dewey’s description, re-branded reflective thinking to include new components that made the thinking process more rigorous, and specifically aimed at making judgments that assisted decision-making and the formation of opinions (Smith, 1953 cited in Ennis, 1964, p.599).

1.1 Motivating thoughts for the combination of critical thinking and chemistry education

The conceptualisation of the study started with a question arising from my own experiences teaching chemistry, namely: why do students fail to use the information they learn in school chemistry to answer questions based on their own experiences? When my students had to combine new and old content, they always found it more challenging to work out what to do with what they knew. It was difficult for them to explain the content they knew. Hence, they asked the same or similar questions over a number of lessons. That placed the question at high priority in the study from the very beginning. Several student questions were not beyond their understanding or ability to provide an answer for rather the students were unable to organise and develop a thinking process – step-by-step or otherwise – in order to move on from the question to the answer/explanation. They failed to connect information from different sources, despite the fact that if asked for each source separately they could provide an answer. Naturally, no teacher expects their students to discover things they do not know without some guidance or help. What is expected, however, is that students develop their ability to make logical connections between knowledge they have and information they have gathered from all instructional sources, and to be able to put them together, like a puzzle, to eventually reveal a bigger picture.

The ancient philosopher Socrates developed a way of guiding his students to a more mature understanding of what they really knew by addressing the fallacies of their arguments through questioning. Socratic questioning aims to elicit a clear and consistent expression of something that is only implicitly known. Freeman (1997), in his colourful book about eponyms, described the cunning of Socrates (p.237), in pretending ignorance and probing his interlocutors, in order expose the paucity of their explanations to, eventually, lead them to conclusions of which they were initially not aware. Paul and Elder (1997) link the Socratic Method directly to CT:

> As a tactic and approach, Socratic questioning is a highly *disciplined process*. The Socratic questioner acts as the logical equivalent of *the inner critical voice* which the mind develops when it develops critical thinking abilities. The contributions from the members of the class are like so many thoughts in the mind. All of the thoughts must be dealt with and they must be dealt with carefully and fairly. By following up all answers with further questions, and by selecting questions which advance the discussion, the Socratic questioner forces the class to think in a disciplined, intellectually responsible manner, while yet continually aiding the students by posing facilitating questions (my italics).

The Socratic question, therefore, prompts thought towards an answer that is not easy and straightforward, rather complicated and enriched with details. In the description of the book “What is Chemistry?” by Peter Atkins (2013), the previewer states that chemistry is a school subject that students find difficult to relate to and that often makes students wonder about the purpose of learning chemistry. Chemistry is a science that attempts to explain the interactions of microscopic particles that cannot be seen or observed, but cause materials to react with and to one another; affecting nature, biology, the environment and so on. Essentially, students have to learn to make judgments about materials, to understand the interactions of particles, to predict what combinations may result by observing, analysing and inferring (to mention a few) from macroscopic phenomena to microscopic forces and interactions. These skills of observation, analysis, inference overlap with CT skills; hence their marriage to chemistry education.

1.2 Premise of the study

1.2.1 Why Secondary School Chemistry?

There were two reasons why the age group of 13- to 15-year-olds was selected. Firstly, there are few studies that have combined CT with secondary science education (with even fewer of these studies focused on chemistry). The emphasis on CT is when students enter higher education when they are expected to shape and share opinions and arguments related to their academic fields. Additionally, universities organise curricula that offer critical thinking courses to help students who enter higher education to acquire mature thought and better mental competency to produce criticality in thinking and decision-making processes. In England, this starts in late secondary education while students prepare for university entry and teachers encourage them to think 'outside the box', be critical when using sources outside the school material, yet, CT is not an immediate aim of teaching at this stage of preparation. From the learning perspective CT is expected to implicitly become one of the students' talents that will help them succeed in entry exams. At college or sixth form, education is designed and oriented towards success in entering university or similar educational institutions. This was the reason why the study did not focus on older students – Years 11, 12, 13 – in fear that their exam preparation might be interrupted and impeded as a result of a CT implementation scheme. In terms of vocational education, lessons tend to be more practical and I do not claim to have enough experience of the demands made on the students when choosing a more practical education.

Younger students in English primary schools were also not selected for the study because students begin to learn science in its distinct principles – physics, biology, chemistry – at around the age of 13. Earlier to that, secondary science education avoids distinctions in order to make the transition from primary school science to secondary school science smoother. For instance, Key Stage 1 science is categorised under the overarching themes of "Plants," "Animals including humans," and "Everyday materials" (DfE, 2013a, pp. 6-13). The curriculum is based on the development of skills such as observations, asking questions, understanding the link between cause and effect, identifying objects, predicting, and even attempting to answer their own questions.

Moving to secondary education, science becomes more fact-based and less dialogical. The students have to learn 'hard facts', that have been proven to be true for years, maybe centuries and little room is left for questioning, offering perhaps alternative perspectives. Hence, chemistry becomes one of the hardest sciences to understand, as what students learn about concepts cannot be seen or experienced at first-hand but may be observed as a macroscopic phenomenon: i.e. change of colour, warming up of a container. It remains quite abstract and maybe hard to understand, so it may dissipate interest. In this case chemistry may be reduced to memorising facts and information without building up a thinking framework to allow for absorption and reflection of knowledge rather than mere retrieval. It was, therefore, the intention of the study to subtly influence the participants towards forming a positive impression for chemistry and its connection to their lives; by increasing levels of curiosity and observation, for example, as well as improving students' understanding of complicated but essential topics, such as the development of atomic theories. The purpose was for students to understand that whatever their ideas on one topic or another, the thinking processes they were using were similar, and these processes could possibly guide them in developing their CT. The tendency to under-think or approach a scientific topic superficially at school would very likely result to approaching another topic in life superficially as well. Ultimately, the skills for CT would be practiced in the chemistry classroom as a guide to understanding science in other practices of life.

1.2.2 Philosophies shaping a study in critical thinking

The study was influenced by different philosophies that made up my experience and perspective of learning and teaching chemistry in a secondary and tertiary context in a Greek school and later university. Methodologically speaking, the methodology of the study was extensively affected by having scientific training as well as the need and ability to combine the scientific frame of thought to that of teaching through logical structures of gathering and understanding knowledge. Scientific training requires a rationalisation of observations and in the field of chemistry it also requires an explanation of the microscopic elements in order to offer an explanation and description of what was originally designed and what was eventually achieved. In chemistry, an experiment that does not yield the expected product is not necessarily a failure if the chemist can explain why the expected product was not yielded and how the production of the unexpected compound occurred. Chemistry is often viewed as a strictly structured field with little flexibility for originality, where the chemist follows a recipe and deals with the outcome.

This view, however, is dismissive of the fact that conceptualising experiments requires good theoretical background, excellent practical skills and a keen eye for detail.

The study was also influenced by logical positivism. Positivism is closely related to the scientific and mathematical frame of thinking, with the foundational stone being Logic or rationality. Rationality has also been a celebrated and much-desired foundation for CT. Logically, therefore, it follows that positivism or – the softer version of it – scientific thinking has extensively influenced the philosophy of CT. A chemist, for instance, may use experience to design an experiment, painstakingly puzzle together the process and create the circumstances that will secure a predicted outcome, yet still find themselves in the position of having to explain the unexpected. An unexpected result requires an explanation, an investigation into the possible causal factors and the design of a new experimental process to eliminate the deviation. In chemistry, an investigation by factor is the norm, and a positivist – in the sense of logical – stepwise process underpins the procedure.

In relation to education, critical thinking may be a prestigious aim on one hand, on the other, practical applications are hard to implement, especially when teachers have to follow a strict syllabus of content. Arguably, CT scholars and champions of Logic have undertaken the task of shaping CT philosophies, which have influenced, and still do, educational reforms for almost a century. In theory, logical positivism builds on the theoretical premise that phenomena, scientific as well as social, can be explained using logic and a mathematical interpretation. For instance, Bertrand Russell (1950) in his article about logical positivism demonstrates – not explains – how the specific type of logical thinking helps in the analysis of social phenomena and the factors that cause those phenomena to manifest in society. Russell (1993), and others, championed science because it could be a trusted method of knowing what to think or believe; it is a way of “dispelling of many traditional beliefs, and the adoption of others suggested by the success of scientific method” (Russell, 1993, p. 1) Science is the epitome of logic. In his article, “Logical Positivism”, Russell (1950) presented the view of “mathematics as the pattern to which other knowledge ought to approximate, and … [how] mathematics, or a not dissimilar type of reasoning, could give knowledge as to the actual world” (p. 4), where the “not dissimilar type of reasoning” refers to scientific inquiry. In practice, the science teacher is assumed to have scientific training and content knowledge and are likely used to using a scientific way of thinking or acting as an everyday teaching practice. Scientific inquiry is practiced in science and makes up a noble and sturdy aim in science education. If disposition is also taken in consideration, demonstrating good scientific skills is likely to inform a career choice. We assume that the majority of science teachers liked science long before they entered formal scientific training and that influenced their decision to become science teachers. Adding the impact of experiences – which Dewey and Russell both support as a formidable influence in science interpretation – it is expected that science teachers master analytical skills, observation, and reflection. Being analytical, however, does not necessarily follow that teaching will be equally analytical. A critically imposed teacher will not influence their students towards criticality unless they plan and organise moments and actions that foster critical thinking.

Moving from a practical science, such as physics, chemistry, or biology, to a humanities-oriented profession, causes certain challenges. The classroom does not resemble the environment of the laboratory of the scientist. Interacting with other people – young ones that are in the midst of their development – is messy, not straightforward and frequently does not go as expected. Working in a classroom demands creativity from the teacher. It also calls for the ability to adjust to adverse circumstances quickly and effectively, for example, if a lesson component, a computer or a screen does not work. These seemingly external factors impact on the flow of a lesson and may often disrupt students' understanding. In a similar fashion, moving from a positivist view of research to educational research ought to allow for some degree of interpretivism in the study. The philosophy of interpretivism allows the awareness of bias, the admittance of looking for something specific in the classroom, for a focus lens to be applied and accounted for.

Investigating interactions among people leaves considerable room for a researcher to attribute attitudes to what they assume are the motives of the participants. This cannot but affect the positivist viewpoint and guide the journey. Action research allowed these interpretations to hold validity, narrate the study and the role the teachers played both as participants and as initiators of the action. Action research also helped to answer to emerging challenges as the study moved from an initial experimental design to one more appropriate for social research. Nevertheless, a degree of positivism has remained in the principles of the study, but it is now to be found in combination with the principles of social research that favour more freedom in design, participation and discussion of the results.

1.3 An overview of the Thesis

To think critically is something that society expects citizens to do well for their individual as well as for the collective wellbeing. This is why it is important to develop CT during the schooling career when students are both impressionable but also demonstrate great capacity for learning. The present study examines whether CT can be practised and enhanced via chemistry, as the two share features towards understanding complicated patterns and using logic and planning to move forward.

An overview of the scholarship in CT can be found in Chapter 2. It includes a discussion of main principles of CT upon which this study was based and how these might be operationalised for a context in education and more specifically English mid-secondary chemistry education. Chapter 3 presents how the study was conceptualised and the premise that chemistry as a subject intrinsically encloses the training for certain of the skills that are considered prerequisite for CT. The relevant skills are also examined in detail and analysed in terms of their quality and usefulness to the development of CT and those aspects that are relevant to secondary school chemistry are revealed and explained.

Chapter 4 presents the organisation of the study, the methodology that advised the seeking of participants as well as the methods that put the study in motion and yielded the data. The methodology follows a dialectic pattern, which permeated the study at all times and allowed the participants to be collaborators and shape their own understanding of best practice. The described approach resonates with the ideal that education promotes democracy and democracy promotes education. The ideal of democracy relies on dialogical practices that are proposed but not imposed. Within the current study, this ideal was used to guide the participating teachers to use more dialogue and allow their students to voice their thoughts more than they did prior to the study.

Chapter 5 is a detailed presentation of the data sets that were gathered. It elaborates why the original idea of the study changed upon collaboration with the different teachers and how this differentiation was beneficial to the study. Education should not be political, yet it is. Keeping the character of education closely linked to the needs of society for progress and well-being is the more noble and less politics’ oriented aspect that this study and most educational research works towards. The data presented in Chapter 5 focused on those aspects of critical thinking that bring a better understanding of chemistry whilst aspiring to achieve a more positive attitude towards chemistry; to make students more able in decision-making on crucial personal and social decisions on scientific matters. It compared the actions of the students and their teachers for the duration of the study; not to benchmark best practice, but in order to discern the most successful attitudes in the students and teachers, to create a model of reference for CT.

The model of reference takes shape in Chapter 6, through a discussion of the findings in a form that will allow the teaching of chemistry to go beyond fact-giving and memorisation towards a more substantial understanding; developing students' use of chemistry in context as well as a critical thinking skillset. Notions of transferability and assessment of skills are challenged and the weaknesses in the study are discussed alongside its strengths. The chapter also aims to show the originality of the study as well as the areas of success.

Finally, Chapter 7 presents the skills and areas of critical thinking that the study showed had the potential to enhance chemistry education, but have not been discussed elsewhere. Chapter 7 also identifies those aspects of critical thinking, which if chosen to be implemented in future studies, they could create a platform that boosts CT as a skillset as well as a disposition.

2.0 CRITICAL THINKING – A REVIEW OF THE LITERATURE

Chapter Objectives

The aim of this chapter is to review the literature on critical thinking. The definitions, notions and different approaches to CT that are included in this chapter have been used to shape and inform the present study. This chapter aims to navigate understanding of the values of CT. There is extensive literature on critical thinking as it has preoccupied men of letters since the ancient times. The literature that is reviewed in this chapter focuses on CT as an educational tool and paradigm in the modern era. Dewey's reflective thinking, the North American tradition and UK practices are explored in detail and from different perspectives. Theory, tools for assessment, character qualities and trainable skills are included in an attempt to present to the reader critical thinking as a concept that has been explored in time.

2.1 Introduction

The tradition of critical thinking in education has been much more prominent in the US than in Europe. The 1996 National Committee on Science Education Standards and Assessment's report (National Research Council, 1996), influenced US policies on science education and critical thinking. It emphasised good thinking, higher-order thinking, reflective thinking and the kind of thinking that involves judgment and active combination of a number of intellectual faculties. Such an approach has ancient origins, but was reintroduced to US education by John Dewey. Dewey (1933) visualised the reflective thinker as a person who could adjust their thinking, decision-making and conclusion reaching through the combination of external information and internal experiences. Dewey's influence on the subject of thinking and thought-formation was significant, as he diverted teaching practices and learning experiences away from memorising a textbook into thinking about the information found in textbooks and making sense of it.

Historically, defining CT has been a struggle and several approaches to meaning-making of CT within education have had different outcomes. Specifically, following Dewey's influential teachings, the CT movement acquired further momentum and strength in the educational practice in a top-to-bottom approach in the mid-40s and full development of CT modules was widespread in the 80s (Paul, 1985). Scholars and movements began to advocate the teaching of CT as a subject of study in its own right in universities, colleges and eventually schools, and time was allocated to practising these 'good skills' (Bensley, 2011) using "criteria in making reasoned judgements" (pp. 2-3). However, McPeck (1981) has argued that too much effort has been invested in defining what skills and practices demonstrate critical thinking without being able to give a precise definition or description of the actual concept in the first place: We "rush over the analysis of the basic concept and … move on to itemising the various skills that it is thought to involve" (p.2). This is not an oversight in the literature. Every attempted definition of critical thinking is either too simple or too complicated: the former leaving a lot to be desired in understanding CT, the latter being too complicated to achieve. For instance, Smith (1953, cited in Ennis, 1964, p. 599) said "Now if we set about to find out what … [a] statement means and to determining whether to accept or reject it, we would be engaged in thinking which, for lack of a better term, we shall call critical thinking." In the same paper, Ennis (1964, p. 599) defined CT as "the correct assessing of statements". To these examples, others can be added: Siegel's (2010, p. 141) version about critical thinking is that it is "often expressed in terms of cultivation of reason or the fostering of rationality". These statements-definitions do not clarify what critical thinking is.

For Lipman (2003), any definition for CT must relate to a description of attributes of the critical thinker, the actor rather than the action. Lipman's four pillars are to be "productive of judgments, guided by criteria and standards, sensitive to context, and self-corrective" (Lipman, 2003, p. 62). Lipman's laconic definition or description still encapsulates observation, analysis and evaluation in the production of judgments, open-mindedness in being guided by evidence, awareness of terminology and terminology barriers according to context, and flexibility to self-evaluate and self-correct. However, for Siegel (2010) any definition of CT must include:

> (1) the claim that the notion is essentially normative in character and (2) the claim that critical thinking involves two distinct components: both (a) skills or abilities of reason assessment and (b) the dispositions to engage in and be guided by such assessments (Siegel, 2010, p. 141).

Siegel's emphasis is on the normative character of critical thinking as an exercise of the thinking process rather than the outcome of a number of cognitive and metacognitive skills, which is a position that draws on the psychological rather than the philosophical/scientific tradition. Paul (1990) takes another route to CT that places the emphasis on the social value of learning to and acting upon thinking critically:

> Critical thinking is disciplined, self-directed thinking which exemplifies the perfections of thinking appropriate to a particular mode or domain of thought. It comes in two forms. If disciplined to serve the interests of a particular individual or group, to the exclusion of other relevant persons and groups, it is sophistic or weak sense critical thinking If disciplined to take into account the interests of diverse persons or groups, it is fair-minded or strong sense critical thinking (Paul, 1990, p. 51)

Paul's CT is complemented by assessing:

1. The problem or question at issue
2. The purpose or goal of the thinking
3. The frame of reference or points of view involved
4. Assumptions made
5. Central concepts and ideas involved
6. Principles or theories used
7. Evidence, data, or reasons advanced
8. Interpretations and claims made
9. Inferences, reasoning, and lines of formulated thought
10. Implications and consequences which follow (Paul, 1990, p.52-53).

Paul clearly and explicitly inserts the ideas of independence and quality into his definition, but he also addresses the ethical responsibility of engaging in CT in a “weak sense” or a “strong sense.” These are important additions in comparison to the other definitions and lists of traits for the critical thinker because Paul’s view of CT engages in the analysis of the emotional factor and impact of being trained to think critically and acting accordingly. The impact of emotions as Paul presents them in CT are reviewed in the next section (2.1).

Nevertheless, the vagueness of the statements on critical thinking do not provide a definition that can be widely used. When trying to make things more specific, two approaches stand out. Firstly, critical thinking is described as a set of skills in which the thinker can be trained. Secondly, the descriptions list character features; dispositions that foster critical thinking. Therefore, we can describe the actions of critical thinking but not the concept itself. The present work offers no better insight in this respect. The need to define the concept, however, is not lessened and, as described above, critical thinking scholars have determined a number of actions that a critical thinking process may contain: observation, analysis, gathering information, evaluating the sources and the information, in order to form an opinion, make a decision or build a supportive argument. This study does not add any clarification to defining critical thinking. The importance of highlighting the confusion in the field serves to frame the chapters that follow and the attempt to clarify the aspects of CT that were studied (Chapter 3), the practical approaches to it that were conceptualised (Chapter 4) and the outcomes that were observed and recorded (Chapter 5).

The definition of critical thinking that was used as a guide to understanding and explaining CT to the participants and collaborators in the study was given by the American Philosophical Association (Facione for APhA, 1990, p. 3):

> CONSENSUS STATEMENT REGARDING CRITICALTHINKING AND THE IDEAL CRITICAL THINKER
>
> We understand critical thinking to be purposeful, self-regulatory judgment which results in interpretation, analysis, evaluation, and inference, as well as explanation of the evidential, conceptual, methodological, criteriological, or contextual considerations upon which that judgment is based. CT is essential as a tool of inquiry. As such, CT is a liberating force in education and a powerful resource in one's personal and civic life. While not synonymous with good thinking, CT is a pervasive and self-rectifying human phenomenon. The ideal critical thinker is habitually inquisitive, well-informed, trustful of reason, open-minded, flexible, fair-minded in evaluation, honest in facing personal biases, prudent in making

> judgments, willing to reconsider, clear about issues, orderly in complex matters, diligent in seeking relevant information, reasonable in the selection of criteria, focused in inquiry, and persistent in seeking results which are as precise as the subject and the circumstances of inquiry permit. Thus, educating good critical thinkers means working toward this ideal. It combines developing CT skills with nurturing those dispositions which consistently yield useful insights and which are the basis of a rational and democratic society.

Facione's definition for the Association does not come in the form of a list and is not limited to a few descriptive lines. The first seven lines provide a definition and a frame for CT, which are then complemented by a complicated, meaning-heavy, yet, quite complete description not only of what critical thinking is but also, what are the expected CT skills the thinker could develop and what a critical thinker is expected to be able to do. This description explicitly supports the idea of independence of the individual in all stages of hatching a thought, notion or question to become an opinion, decision or belief.

2.2 Models for Efficient CT

Though plentiful definitions and descriptions have been provided for CT, those short lines or lists of skills only scrape its surface. The reasons why CT is important and why it is important to understand, practise and teach, still need to be analysed. Not many CT scholars have attempted to expand on their initial definitions of CT to aid the creation of a framework for CT development and practice, but there are some works that it is imperative to mention. Ennis (1996a) has produced a CT framework, a set of six ingredients that are given to the reader as a guide to CT. The author names the framework FRISCO, an acronym made up of the initials of the six components: Focus, Reasons, Inference, Situation, Clarity, and Overview. Paul (1990) has also offered guidelines towards an improved teaching practice for CT development through education and McPeck (1981) has produced a mathematical model that would fit to a Logic tradition. Finally, tertiary education designers and academics who are trained in Logic, Philosophy, and Reasoning have recognised the need for undergraduate students to develop their CT skills and have designed university undergraduate modules to train their students to become critical thinkers. These works are analysed in detail in the sections that follow (2.2.1, 2.2.2, 2.2.3) in order to highlight the strengths and weaknesses of attempting to develop critical thinking; either as an individual or through formal and informal instruction. The models are presented in a pre-designed order to illustrate how the scholars have influenced the field with their proposed models or model-like ideas and how these concepts have been implemented in practice in educational contexts (section 2.4).

2.2.1 FRISCO

Ennis (1996a) links CT to democratic procedures. The free mind, the mind that can freely decide on social and political issues, can think clearly *before* making the decision and justify the decision *after* it is made. Democratic structures in the western cultures are upheld by the freedom of citizens to choose their representation, and therefore to be able to both form and explain the decision of such a choice, stands upon the ability to critically review the choices. According to Ennis (1996a), "critical thinking is a process, the goal of which is to make reasonable decisions about what to believe and what to do" and that "we have a public responsibility to try to make reasonable civic decisions that I, to try to think critically about civic matters, and to help others do so as well" (preface). Thus, the aim of the FRISCO model is "[to cover] both the evaluation and development of positions and arguments" (Ennis, 1996a, p. 364), to help individuals become critical thinkers that can sustain the critical decision making for themselves as well as aid others in doing so. Ennis's guidance and advice specifies how to be critical when writing a paper, when arguing a point in a discussion, in team-work situations, when making a presentation and so on. The six elements in Ennis's mental checklist are analysed in categories and subcategories, based on the situation at hand as well as the criteria that arise or are inherent in the situation. A detailed presentation of the model is attempted below.

FRISCO can be said to be a steps' process. It is presented in a specific order, designed to avoid confusion and reduce the feeling of being overwhelmed by the many new concepts (Ennis, 1996a, p. xix). Focus is step 1 in the FRISCO model and relates to finding the point of focus of the situation. The critical thinker should zoom in to the question that she tries to answer. When the situation is clear, the focus is self-pronounced, in the form of problem-solution. Caution is advised in ambiguous situations where focus is not clearly defined and focusing on the wrong question inhibits the process. Step 1 is naturally followed by another question: why answer this question? (Ennis, 1996a, p. 5) and investigates the reasoning behind asking such a question. The reasons given are: the motivation that leads to the action of gathering information, experimenting and viewing data which are used to support an explanation and provide arguments for the position held or unsubstantiated, redirects the critical thinker to further investigation (open-mindedness).

The third step, inference, entails the risk of judgement. Inference, according to Ennis, is whether and how well the reason could support a conclusion (Ennis, 1996a, p. 6). Step 3 in this case builds an argument and is clearly oriented towards the end result: not only making a decision on what to believe but also having the support necessary to convince others who may dispute the validity of the decision or opinion. Inference for FRISCO is an inception of reasoning: what reasons the individual has to believe the reasons that support the argument. Inference in the FRISCO conceptualisation is different to what it is in other relevant literature. In the CT assessment tools presented in Section 2.3, inference is the process of coming to a conclusion when there is sufficient but not all necessary information. For Ennis, however, inference is undertaken early on in the critical thinking process. Possibly, this means that the individual may be inclined towards an opinion early on, which they look to critically think on and evaluate.

The model continues with a focus on the situation, which Ennis separates from the need to think about a belief/decision. The thinking that focuses on the belief can then be traced in situations that have several dimensions: social, emotional, emotional for other people in the situations, the environment and so on. Because the situation can be so broad, clarity, the next step is important; where all the previous steps are incorporated to make up the larger picture. The final step of the model is the overview, whereupon the critical thinker reviews the previous steps and decides whether a valid decision can be reached or whether more deliberation on the previous steps is required.

Despite the fact that the book offers a valid insight of the rigour and effort invested in making decisions, FRISCO is not a straightforward, easy-to-follow model. It is, therefore, not used in the study. The five elements of FRISCO presented in the first chapter are followed by another 12 chapters of details the critical thinker needs to keep in mind and be agile about in order to miss pitfalls. The model is unsatisfactory in its attempt to be simple yet detailed and complete, as the presentation of it in the book clearly demonstrates that the simple five elements are far from simple if the individual aspires to become a competent critical thinker. FRISCO is rigid and creates confusion which prohibits its use in an educational setting with several dozens of students. It is however, the only model that offers guidance for the individual to develop their critical thinking outside an instructional or educational situation.

2.2.2 Paul’s instructional approach to teaching CT

Paul's approach to instruction is fundamentally different to Ennis's as he believes CT to be a 'principled' rather than a 'procedural' approach (Paul, 1990, p. 240) as no number of steps can ensure that students will become critical thinkers. To change the way we think requires a change in the way we perceive the world around us; changing our interpretations of the stimuli received and our responses to those stimuli. Paul’s instructions to teachers and curriculum designers resonates with the values of developing CT in this study and will act to guide the relationship between the theory and practice of CT

Paul’s (1990) book on good practice for CT devoted a section to how to teach critical thinking. The book was directly addressed to educators, school teachers, and college and university lecturers; and focused on the actions educators should undertake to develop CT in their students and the impact those actions will have on the students. For Paul, there are specific attributes that can make the students critical thinkers and those are:

1) that students learn *what* to think only as they learn *how* to think,
2) that one gains knowledge only through thinking,
3) that the process of education is the process of each student gathering, analyzing, synthesizing, applying, and assessing information for him or herself,
4) that classes with much student talk, focused on live issues, is a better sign of learning than quiet classes focused on a passive acceptance of what the teacher says,
5) that students gain significant knowledge only when they value it,
6) that information should be presented so as to be understandable from the point of view of the learner, hence continually related to the learner's experiences and point of view,
7) that superficial learning is often mis-learning and stand as an obstacle to deeper understanding,
8) that depth is more important than coverage [of content],
9) that students often provide correct answers, repeat definitions, and apply formulas while not understanding those answers, definitions, or formulas, and
10) that students learn best by working together with other students, actively debating and exchanging ideas (Paul, 1990, p. 233).

To achieve the conditions that will allow for the development of the student as a critical thinker, Paul suggests a number of important changes to educational contexts. The first and most imminent is the redesign of curricula, the foremost frame of educational context. For example, the current English Key Stage 3 Science curriculum states the goals for CT in vague terms:

> The principal focus of science teaching in key stage 3 is to develop a deeper understanding of a range of scientific ideas in the subject disciplines of biology, chemistry and physics. Pupils should begin to see the connections between these subject areas and become aware of some of the big ideas underpinning scientific knowledge and understanding. (DfE, 2013, p. 2).

For Paul, expecting students to develop the ability to combine ideas, concepts and knowledge from different areas of their student experience (even within the same subject or course) is a CT exercise that needs to be openly expressed but also viewed from a philosophical point of view, so that students understand not only the context but also the way to make sense of the context within their experiences. Curricula composers ought to state explicitly that CT is an important objective of education which can be achieved through specific activities that provide opportunities for the sustainability of thought (Paul, 1990, p. 236). According to Paul, CT is the only way for knowledge retention. Therefore, if students are not driven to think for themselves and instead expect the answers from their teachers, the threshold of effort is much lower and the knowledge retention becomes temporary and superficial (Paul, 1990, p. 239). It is therefore, the teacher's job, the didact's duty to ensure that students are provided with enough opportunities to first develop their thinking and, progressively, own their thoughts, and showcase the strength of their thinking by expressions within the educational context (Paul, 1990, p.239).

Paul suggests that all learning be based on debating and arguing points, that students engage in discussions that help each other progress in their thinking by negotiating points of discussion, exchanging ideas, and so on. It is, admittedly, an approach that requires the teacher to remain agile and active in fostering the environment for discussion and negotiation of meaning via activities that incorporate the critical element, and requires the students to learn to look for the intricacies hidden in a text they read or a text they produce (Paul, 1990, pp. 240-41). It is also a process that Paul recognises cannot be effective in a short period of time, as the proposed exercise aims to change and enhance the students' critical thinking; and thinking in itself is not developed overnight.

Teachers are at the heart of Paul’s model as they are the ones required to implement the changes and adjust their practice. Ironically, it could be presumed that the students are much less discussed and the impression gained is that they are the passive recipients of a teaching scheme that wants to keep them actively participating, but does not give them much responsibility. This, however, would not be an accurate reading, but one that is skewed by the fact that Paul chooses to direct his instructions to the teachers, as they are invaluable allies; and without their willing participation the approach would not succeed. Nevertheless, Paul fails to address what happens, in terms of CT development, when the students are away from the influence of the educational context, how the individuals are meant to sustain their CT development when they are not with an instructor, a teacher or a mature thinker directing their meaning-making.

2.2.3 McPeck’s views on CT instruction and learning

McPeck (1981) provides yet a different approach to developing CT to those of Ennis and Paul. In his book *Critical Thinking and Education* (McPeck, 1981) he devoted some effort to providing an understanding of CT and offered a tentative plan on how to approach its teaching and learning. McPeck is fundamentally against the teaching critical thinking outside of context (McPeck, 1981, p. 2-4). To teach students to think lacks coherence if it is not directed towards how to think in history or biology or a concrete area: “to think about nothing in particular is equivalent to not thinking at all” (McPeck, 1981, p. 3). McPeck’s CT always revolves around a problem (X), an activity or a subject area that can be thought of critically. Each of these instances is made up of criteria that will induce the “correct application” (McPeck, 1981, p. 6) that will allow for scepticism – the most important component in the approach – and suspension of judgment. McPeck did not give detailed descriptions of the criteria as each X gives rise to a unique set of circumstances that cannot be reduced into a list. However, the model of CT that is proposed followed the principle; that for every X for which a student (S) has some evidence (E), a proposition (P) or action within X can be stated:

> Then we can say [about S] that he is a critical thinker in area X if S has the disposition and skill to do X in such a way that E, or some subset of E, is suspended as being sufficient to establish the truth of viability of P (McPeck, 1981, p. 9).

In simple words, when the individual possesses profound knowledge and understanding in an area (X) and can retrieve evidence that justifies an action within that area, then they have the ability to think critically and act on a number of such actions. For McPeck, the competence of critical thinking mostly relies on some – unclear – degree of expert knowledge in the given area and when that component is not there, it can hardly be expected that the individual will have a successful critical thinking approach. However, success as an outcome of using CT is not a prerequisite. McPeck leaves room for error to be made and justified in the process of acting as a critical thinker. In that respect, McPeck's approach is unique in incorporating the possibility of mistake into the process of CT. In the context of education when the student is expected to get answers wrong, most other scholars do not clarify whether they expect CT to be a vehicle for making correct judgements, 'correct' meaning the right answer according to the textbook, the teachers' training, the general compilation of knowledge.

McPeck (1981) did not stray far from the use of what he called, "intellectual components" (p. 11); such as methods, strategies and techniques and the need for skills to be cultivated towards CT as they allow students to conceive both the knowledge and the way it was constructed. A distilled set of skills, which are only inferred and not identified, is what educators should strive to teach their students, and are possibly related to logic and reasoning, questioning both for concept-building and for testament of knowledge (McPeck, 1981, p. 11-12). Finally, McPeck (1981) devoted considerable effort to trying to distinguish logic from critical thinking. Logic does not automatically make the individual a critical thinker, as other components also need to be present: training, skills and, most importantly, context.

McPeck has been criticised for his conceptualisation of critical thinking and the way he presents CT to be an entity, which is unable to survive without a host; the host being a problem that requires solution (Paul, 1990, p. 411-420). Admittedly, McPeck's critics have not managed to disprove his claim that CT requires a specific enough context. However, McPeck has provided what reads like an unfinished draft of his conceptualisation of critical thinking and how it is defined. The McPeck approach to CT has a mathematical outlook which was promoted as the only viable approach. However, its mathematical character makes the intended formula rigid and inflexible. In a subject for which flexibility is crucial, the inadequate definitions of the other conditions framing the formula render it a poor tool for this study.

2.3 Disposition and Training towards CT

Part of the debate surrounding CT has always concerned what aspects, if any, of CT can be taught and those which are perhaps innate. This has motivated scholarly work to look into whether critical thinking can be a trainable feature (see also sections 2.2.1-3 above) or it is best accomplished when based on cultivating character features and dispositions.

The relevant literature talks extensively about trainable skills such as analytical thought, evaluation, combination of information and other skills that have made up definitions of CT (Ennis, 1962; 1964; 1990; Siegel, 1988; Halpern, 1998; 1999; to mention a few). Most scholars provide lists of skills that could be progressively improved and are echoed in science curricula, which envision students will become more competent in the scientific way of thinking, improve their analytical skills, the evaluation, the ability to use different methods of experimenting and data gathering; all of which can be cultivated via activities. For instance, (i) the ability to observe closely, (ii) the ability to follow an order of actions that can help the individual feel confident and comfortable in making a decision, (iii) the ability to train oneself to distinguish between reliable and unreliable sources of information, are based on experience and practice. For example, a person who encounters the signs of a storm for the first time might not seek shelter from the approaching rain but upon repetition of the experience it is expected that the person will choose a course of action (Dewey, 1933, p. 9-10).

For Snyder and Snyder (2008), critical thinking within the educational context is any activity that does not require the students to memorise; rather, students are motivated "to analyze, synthesize, and evaluate information to solve problems and make decisions (think)" (Snyder & Snyder, 2008, p. 91). Similarly, De Bono's (2016) Six Thinking Hats method supports the notion that CT can be learnt because "critical thinking consists of seeing both sides of an issue, being open to new evidence that disconfirms your ideas, reasoning dispassionately, demanding that claims be backed by evidence, deducing and inferring conclusions from available facts, solving problems, and so forth," (Willingham, 2007, p. 8) and students can be trained to do so.

In contrast, Ennis (1996b) suggests human beings have critical thinking dispositions and the "tendency to do something, given certain conditions" (p. 166) and "the disposition toward critical thinking is the ***consistent internal motivation*** to engage problems and make decisions by using thinking" (Facione et al., (1997), p. 2, bold-italics in original). CT dispositions are different from skills for CT, and resemble the formation of habits that enable critical thinking as an exercise. For Siegel (1988), dispositions are ultimately self-motivating drives to assess reason, a willingness to stay true to a principle both in theory and in practice, the rigour and desire to seek out evidence and the justification or refutation of judgments. Siegel (1988, p. 39) called this a "critical attitude" or "critical spirit", and the choice of words showcases the sensitivity of character towards those attributes. Hanscomb also admitted that dispositions are interrelated and therefore one disposition may be connected to numerous others, and chose to focus on a select list of virtues: “love of truth, open-mindedness, flexibility, modesty, self-knowledge, meta-cognition, and […] ‘dialogical dispositions’” (Hanscomb (2017, p. 59).

In Dewey’s (1933) view disposition is an attitude that develops “the *habit* of thinking in a reflective way” (p. 33, italics in the original), it is a “nexus of attitudes, intentions, values, and beliefs … [that] are among the distinguishing features of one's character or personality” (Facione, 2000, p. 63). The difference between dispositions and skills is that the former can foster the development of latter (Dewey, 1933, p. 34), skills, on the other hand, however elaborate they may be, cannot develop the former. Scholars’ claims on dispositions and skills, therefore, tend to support the view that the development of CT is based on both these features and one cannot be sustained without the other. For instance, CT abilities (a.k.a. skills) for Ennis were: to observe, to make judgments, to plan experiments, and to develop ideas and alternatives to those ideas (1996a, p. xviii). These, however, should be complemented by “attitudes and inclinations” (dispositions) such as love for truth and justice, representing a position with honesty, and being mindful and respectful of the positions of others (Ennis, 1996a, p. 9). Dewey’s (1933) open-mindedness, whole-heartedness, and responsibility, must be followed by the competence on observation, data collection and experimenting, hypothesising and testing the hypothesis. In that sense, it is pointless to argue skills or disposition, and instead we should argue, skills and disposition.

2.4 Overview of Models, Dispositions and Skills

The models presented in section 2.1 demonstrate the vigorous and multifaceted efforts that CT scholars have invested in informing the literature as well as providing theoretical guidance for educators and educational institutions towards developing CT. Upon review of purposes and presentation, however, they leave room for ambiguity, lack of clarity and fall short of expectations that any one of them is complete and usable in a secondary chemistry classroom. That said, each of the models has an effect on the conceptual model of the present study. FRISCO, for instance, is a structural model with definitive elements which offer enough information to build upon for self-development as a critical thinker. The six components are not an optimum choice of focus for a model or perhaps the way they are presented leaves the reader in confusion and inability to comprehend the way ahead, which is the reason it is not adopted in this study. Paul's instructional approach, on the other hand, leaves a formidable impression for conceptualising how to talk to teachers and educators about critical thinking, how it adds value to teaching practice and it can empower students towards becoming more critical in their educational career. It does not explore CT in the classroom from a practical approach. It remains theoretical and philosophical and as such it is used to firm the theoretical background of the study. Paul's model requires further layers to be added in order for the theory and philosophy of the study to take the shape of a tangible practice. McPeck's logical model provides new frame and guides towards practical considerations that should be taken into account in a CT-oriented teaching and learning approach. The logical and hard-to-implement, single-dimentional design offers an insight on what to avoid in the practice of CT development, either from the teacher's point of view or the student's. The impact of the McPeck model is the contribution towards inserting new dimensions in teaching or learning CT that allows for mistakes and level of expertise.

Along with the models, CT requires the development and conducive nurturing of dispositions for open-mindedness, rationality of thought, emotional strength to accept new evidence and possibly alter a stance, criticality in making judgements and adopting opinions. These virtues can foster the coaching and training of skills for CT, such as analysis, evaluation, combination of data and information, building and presentation of argument, and so on. There is one thing that is clear from the literature investigation, cultivating CT and developing students to become critical thinkers is not an easy, straightforward task and even the seminal scholarship that has been presented thus far leaves ample room for doubt, on one hand, and on the other; creativity and opportunity for design of a novel approach for the introduction of CT in the school context for both students and their teachers. In theory, critical thinking is both comprehensible and applicable. In practice, the nuances of real circumstances complicate its application of the theory that is pure in the mathematical sense. There is, however, no reason why the application should abide by purity of the theory. The theory in this case serves as a model for guidance and as such it informs the present study.

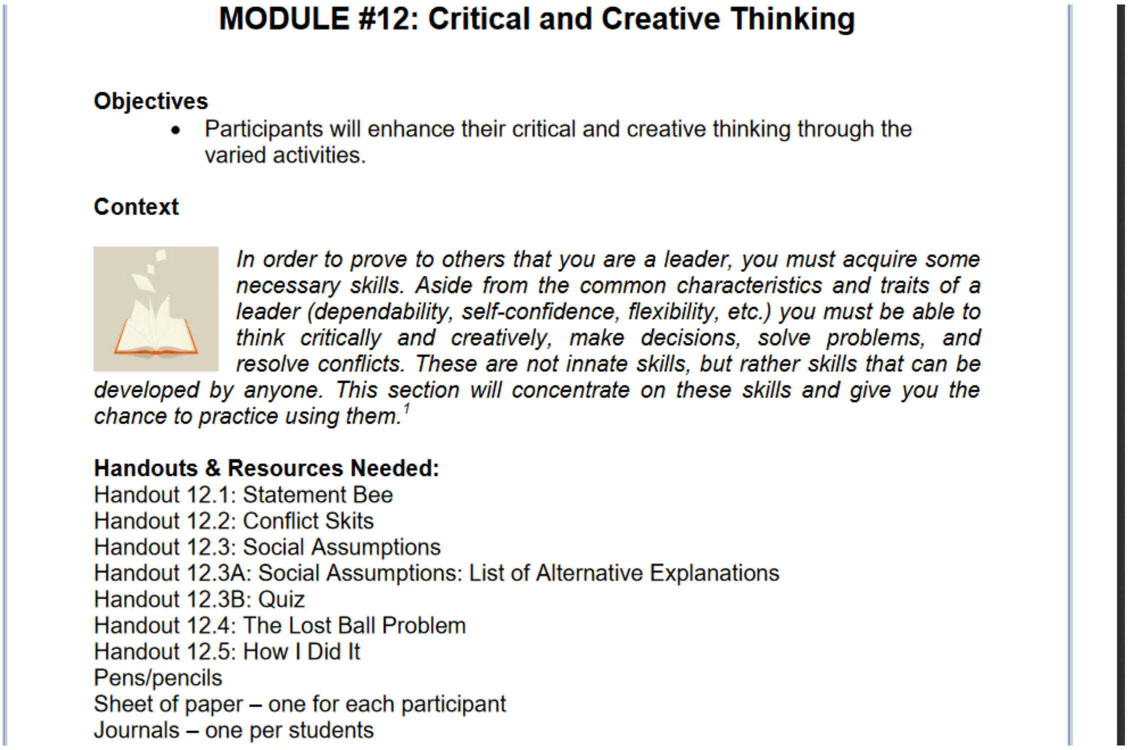
2.5 CT Teaching and Assessment

The development of CT via education brings forth the need to organise teaching practices as well as assessment to gauge the success of teaching and learning. As abstract an idea as CT is, all CT scholars agree that CT should be learned for the benefit of the student, the wellbeing of the citizen and the progress of society, democratic structures, and so on. The debate that ensues from this agreement, however, is how to teach – and learn – to think critically and how to best measure outcome.

2.5.1 Formal or Informal CT, Within or Outside Context

The alternatives in regard to teaching are either CT taught as a separate course (formal, organised and named CT training), outside of specific context, or CT taught within context, planned to happen within a field of education, i.e. chemistry, as an additional – not separated – educational aim. Halpern (1999), similarly to Ennis, supported the idea that CT can be taught outside of context and designated higher education modules can enhance undergraduates' thinking skills and abilities. Rather than focusing on the teaching of CT, the outside-of-context approach aimed to help students learn to transfer good thinking habits across disciplines and modules focused on the transferability and maximisation of CT capital from an area of expertise to an area of less expertise (Halpern, 1999, p. 70). An example of a CT module can be found in Appendix 3 and an overview of it in the picture below (Image 1). The example (Image 1) based the activities on presenting students with scenaria that required a decision, an inference, retrieval of evidence and so on, and trainees were guided by certain principles to go through the process of making sound decisions.

In the example below module activities favoured an open-minded approach to understanding and producing statements, concentrating on the pursuit of truth and making sure that opinions were not formed upon suggestions rather based on evidence that has been gathered and assessed. The module delivery design was based on a facilitator providing situational prompts that students worked on complemented by quizzes provided but not regulated by the facilitator, instead students self-regulated their actions. This module description, which is not the only one of its kinds is quite complete in its layout providing a theoretical and philosophical backbone – open-mindedness, pursuit of truth resonating with disposition – complete with activities for practice – facilitator, perception of statements, assessment of suggestions relating to skills.



MODULE #12: Critical and Creative Thinking

Objectives

- Participants will enhance their critical and creative thinking through the varied activities.

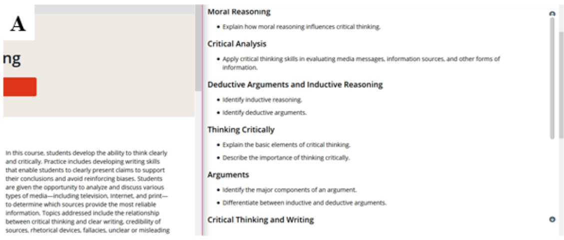
Context

In order to prove to others that you are a leader, you must acquire some necessary skills. Aside from the common characteristics and traits of a leader (dependability, self-confidence, flexibility, etc.) you must be able to think critically and creatively, make decisions, solve problems, and resolve conflicts. These are not innate skills, but rather skills that can be developed by anyone. This section will concentrate on these skills and give you the chance to practice using them.[1]

Handouts & Resources Needed:
Handout 12.1: Statement Bee
Handout 12.2: Conflict Skits
Handout 12.3: Social Assumptions
Handout 12.3A: Social Assumptions: List of Alternative Explanations
Handout 12.3B: Quiz
Handout 12.4: The Lost Ball Problem
Handout 12.5: How I Did It
Pens/pencils
Sheet of paper – one for each participant
Journals – one per students

Image 1: Module overview for CT (source: https://www.aspira.org/sites/default/files/U_III_M_12_ct.pdf)

Despite the professed intention, Halpern failed to untie the teaching of CT from a context as CT was pronounced to be “purposeful, reasoned, and goal-directed” (Halpern, 1999, p. 70; 1998, p. 450) and she failed to explain how goals are detached from educational aims, or any aims for that matter, or how these aims might be removed from educational content. Halpern’s and other scholars’ assertion that CT can happen outside of context , the claim that CT can be taught or trained abstractly comes down to arguing the definition of context rather than the essence of the debate. The abstract approaches that Halpern – and Ennis – has used in the literature still use contextualised, idealistic scenaria for training purposes. The sample-module above (Image 1) provides a critical and creative thinking context for acquiring leadership skills. Other examples (Image 2) are for studies in education, developing criticality for everyday instances within the social sciences, and so on. One instance targets the development of skills without further specificity – similar to FRISCO – still using contextualised scenaria. Therefore, the criticism of Halpern’s or subsequent attempts to develop out-of-context modules is whether they ever aimed to teach critical thinking, or a set of skills that could be assessed against relevant criteria of purpose on each occasion.



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In this course, students develop the ability to think clearly and critically. Practice includes developing writing skills that enable students to clearly present claims to support their conclusions and avoid reinforcing biases. Students are given the opportunity to analyze and discuss various types of media—including television, Internet, and print—to determine which sources provide the most reliable information. Topics addressed include the relationship between critical thinking and clear writing, credibility of sources, rhetorical devices, fallacies, unclear or misleading

Moral Reasoning

- Explain how moral reasoning influences critical thinking.

Critical Analysis

- Apply critical thinking skills in evaluating media messages, information sources, and other forms of information.

Deductive Arguments and Inductive Reasoning

- Identify inductive reasoning.
- Identify deductive arguments.

Thinking Critically

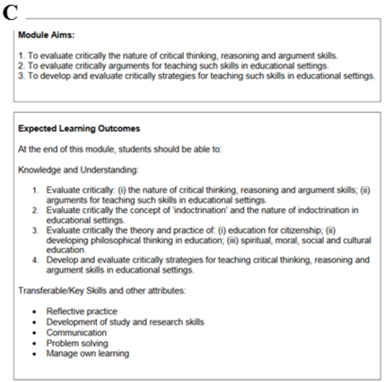
- Explain the basic elements of critical thinking.
- Describe the importance of thinking critically.

Arguments

- Identify the major components of an argument.
- Differentiate between inductive and deductive arguments.

Critical Thinking and Writing

A. Example: Overview and Objectives of CT course aiming to train skills outside of specific context (source: http://www.phoenix.edu/courses/crt205.html)



Module Aims:

1. To evaluate critically the nature of critical thinking, reasoning and argument skills.
2. To evaluate critically arguments for teaching such skills in educational settings.
3. To develop and evaluate critically strategies for teaching such skills in educational settings.

Expected Learning Outcomes

At the end of this module, students should be able to:

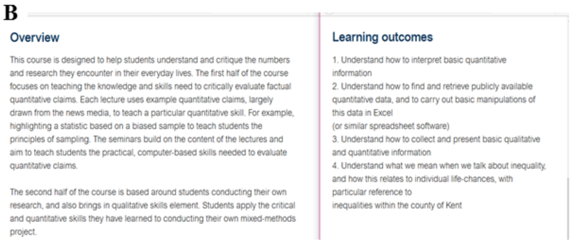
Knowledge and Understanding:

1. Evaluate critically: (i) the nature of critical thinking, reasoning and argument skills; (ii) arguments for teaching such skills in educational settings.
2. Evaluate critically the concept of 'indoctrination' and the nature of indoctrination in educational settings.
3. Evaluate critically the theory and practice of: (i) education for citizenship; (ii) developing philosophical thinking in education; (iii) spiritual, moral, social and cultural education.
4. Develop and evaluate critically strategies for teaching critical thinking, reasoning and argument skills in educational settings.

Transferable/Key Skills and other attributes:

- Reflective practice
- Development of study and research skills
- Communication
- Problem solving
- Manage own learning

C. Module aims and objectives for CT in UG and MA Education degrees (source: https://www.glyndwr.ac.uk/modules/education/EDS701%20Teaching%20Crit%20Thinking,%20Reasoning%20&%20Arg%20Skills.pdf)



Overview

This course is designed to help students understand and critique the numbers and research they encounter in their everyday lives. The first half of the course focuses on teaching the knowledge and skills need to critically evaluate factual quantitative claims. Each lecture uses example quantitative claims, largely drawn from the news media, to teach a particular quantitative skill. For example, highlighting a statistic based on a biased sample to teach students the principles of sampling. The seminars build on the content of the lectures and aim to teach students the practical, computer-based skills needed to evaluate quantitative claims.

The second half of the course is based around students conducting their own research, and also brings in qualitative skills element. Students apply the critical and quantitative skills they have learned to conducting their own mixed-methods project.

Learning outcomes

1. Understand how to interpret basic quantitative information
2. Understand how to find and retrieve publicly available quantitative data, and to carry out basic manipulations of this data in Excel
(or similar spreadsheet software)
3. Understand how to collect and present basic qualitative and quantitative information
4. Understand what we mean when we talk about inequality, and how this relates to individual life-chances, with particular reference to
inequalities within the county of Kent

B. Overview of CT module for Social Science and Wild Choice courses (source: https://www.kent.ac.uk/courses/modules/module/SO341#overview)

Image 2: Additional module-examples for CT in university education

The issue remains that even when all students undergo the same formal instruction of CT and the same exercises for CT – or CT assessment – they will still hold different points of view on the same topic as reasonable and indeed justifiable to them. Teaching CT formally, as a stand-alone subject translates to teaching a set of skills presented. The expected learning outcome is for students to learn to practise the critical way of thinking as a habit not as an exercise. Otherwise, once the stimulus is expired, in this case the formal instruction, the outcome will cease.

An informal approach, on the other hand, is organising opportunities for practicing CT skills within a specific context. The aim of such an endeavour apart from developing the skills, would be to foster a conducive environment to help grow the disposition, acquire longer-lasting expertise in the new area of knowledge, learn to communicate and interact with peers and experts – fellow students and teacher respectively. This approach benefits students who mature slowly or do not exhibit the disposition for CT to be given a chance to do well in a subject even if their CT skills are underdeveloped. This is perhaps not ideal, however, it is a fairer chance for assessment of students' abilities beyond CT. It can hardly be expected for such an ill-defined concept as is critical thinking to be as easily transformed into a school or college subject. For the purpose of this study, education for critical thinking, as Siegel (1988, p. 6) suggests, is traded in for critical thinking in education; the latter to be understood as learning CT by learning to observe, assess, analyse, evaluate evidence, etc. in the reality of the classroom.

2.5.2 Critical Thinking Assessment

Assessment is an inseparable part of education. It is used as a progress tool as well as a device to focus on critical points and hone skills. Most importantly assessment is used as measurement for effectiveness of educational practices. To complete the purpose and fulfil the aims of this study, it was necessary to have a way of depicting and measuring CT as it happened. To do that effectively, it was first vital to investigate what was available in the literature in terms of measuring and then decide if the existing tools were appropriate for the study.

Critical thinking assessment resulted from the need to measure the success of the CT formal and informal teaching. As the literature on CT has become more insightful and specific, CT scholars have moved from the task of describing and explaining critical thinking and the ideal critical thinker to assessing the progress of individuals who undertake the exercise. Ennis's (1993, p. 180) revised list of critical thinker characteristics appears to be motivated by the production of a method of assessment, targeted at teachers and their efforts to teach a set of skills, rather than proposing a model for assessment of CT. Matching the list of features that characterise the critical thinker, Ennis (1993) suggests that a clear definition of CT is required before embarking on looking for a test. He, then goes on and enumerates the reasons why an assessor would choose to assess CT skills: (a) improving skills, (b) giving feedback on progress, (c) providing motivation, (d) better educating teachers on CT teaching, (e) research purposes and so on (Ennis, 1993, pp. 180-181).

There are several CT assessment tools that have been widely used. The first such assessment tool developed in Europe and is called Watson-Glaser Critical Thinking Appraisal (W-GCTA). The W-GCTA examines five specific areas: Inferences, Assumptions, Deductions, Interpretations and Arguments (copy of the booklet can be found in Appendix 5, found in AssessmentDay and TalentLens – online sources). Inferences are defined as "conclusion[s] drawn from observed or supposed facts," assumptions are "something which is presupposed or taken for granted", deductions are not defined clearly, instead the test-taker has to decide whether a conclusion can be reached based on the provided information, and interpretations mean “to judge whether or not each of the proposed conclusions logically flows beyond a reasonable doubt from the information given” (AssessmentDay booklet, pp. 2, 9, 14, 22). Finally, for arguments the test examines the ability of the test-taker to distinguish between a strong argument or a weak one (AssessmentDay booklet, p. 27). The instructions advise against using the test-taker’s general knowledge and try “not to let your own opinions or prejudices influence your decisions” (AssessmentDay booklet, pp. 14, 27).

Other assessment tools for CT are the “California Critical Thinking Skills Tests” (CCTST, found in Insight Assessment and STELLAR – online sources) and the Cornell Critical Thinking Tests (CCTT) developed by Ennis, Millman and Tomko in the US (The Critical Thinking Co, 2017). Understandably, each of these tests has been designed to test the abilities of test-takers using plausible contextualised scenaria. However, the forced pseudo-authenticity makes the use of the tests dubious and reinforces the question whether the purpose of teaching CT is to help the student recognise the impact of personal bias when forming an opinion/reaching a conclusion, or a standardised tool for excellence. An overview of the assessments creates a new set of questions that need to be asked regarding the value of critical thinking and, separately to that, the value of teaching or training towards critical thinking. Each test booklet is a package for training before the test, which in itself raises the question, what exactly is assessed: the ability of the student to follow instructions and perform in the test or the ability of the student to perform in a situation that necessitates CT. Upon fostering CT in an educational or instructional environment, a logical assumption would be that there is no need to test as the results of a successful or unsuccessful process should be obvious; not through a test but from spontaneous manifestation of both skills and dispositions in different authentic contexts. This supports McPeck’s point of view for the need of authentic context on one hand and for arguing that developing the ability to think critically does not mean that the student will always get the right answer. Practically, it means that an investigation and effortful process would be needed before the adoption of an opinion or view. A test, or any type of assessment, however, significantly restricts the margins for error; especially when each test or assessment tool comes with a set grid of answers. From the examination of the tools and the attached purposes, it is questionable whether any design of assessment would successfully assess a critical thinker who has not used the recommended training package.

2.5.3 Critical Reflection on CT Assessment

As has been described above, the available assessment tests leave intricate, more complicated skills untested as there is little chance for the test-taker to *elaborate and explain* how they may combine knowledge, experience, thought and the momentum of the moment influence their thinking process and outcome. This is because such tests do not allow students the space to demonstrate the indicators of critical thinking, namely: (a) the competency of producing – in writing or verbally – coherent arguments and explanations (see Chapter 3); (b) being able to understand and discuss conflicting points of view (Lipman, 2003) and (c) becoming more confident in making decisions in areas that the individual has little prior knowledge (Ennis, 1996a). As Ennis (1993, p. 181) observes, "[m]ost critical thinking tests … typically miss much that is important in critical thinking" as the test-taker is more concerned with finding the expected right answer than using their own CT skills to provide an answer that makes sense to them. CT is portrayed as an esoteric process that allows for reflection, evaluation or re-evaluation, an internal dialogue that *may* be externalised depending on circumstance and time.

Time is of essence in terms of maturity of thought, through process and understanding; circumstance is of essence as it influences the emotional aspect of making a decision. And any kind of assessment usually involves a level of anxiety in the effort to provide the answer that the assessor has recorded as correct. The test-taker focuses, or rather is distracted by, both these factors, which by design block reflection and internal dialogue. Finally, in most educational settings a test is designed to check on the progress of a test-taker, to evaluate said progress and tests generally mark the end point of the educational process. However, CT is not something that we would expect a student/test-taker to stop practising after the test. To test for CT skills, therefore, seems to be countering the essence of the instruction. There is always the possibility that CT can be assessed, but the appropriate tool for the assessment has yet to be devised. A universal type of assessment does not suffice to cover the range of skills, the creativity of the mind, or the maturity of thought that CT requires and therefore the universal tools that have been mentioned in the Section 2.4 are not used in the study.

For an assessor to be able to assess CT, it is expected that the assessor themselves have undergone some training and have mastered the CT skills. The assessors in the study would be the teacher participants. However, it is a false assumption to expect the teacher participants to be trained CT assessors and more aware critical thinkers than their students. In fact, as CT is not a concept that is openly mentioned in the curriculum – it is only implied via the description of a set of skills – it is not expected that teachers, albeit their teaching experience and training, have been actively practising CT in the classroom. Therefore, they are not seen as assessors. They are, however, seen as experts in knowing the abilities of their students and as such they are considered able interpreters of the changes that their students manifest and possibly are more able to explain those changes. The influence of CT can be matched against the explanations of the changes in the students. The discussions with the teachers manifest the way the teachers' way of thinking has been influenced by CT – as a concept – permeating their teaching and classroom practices.

Summary

Reviewing the work of the most prominent scholars of critical thinking, it has become clear that theory on CT is vast and inconclusive. Though terminology is mostly agreed upon, the polyphony of perceptions of critical thinking adds dimensions that enrich the CT skills and dispositions of the diligent student. There appears to be no singular correct way to teach or learn CT, as Sternberg (1986) comments “there are so many accounts of critical thinking, … [that] so often say similar things in different ways, or even occasionally different things in similar ways” (p. 7). This perhaps helps to make sense why the review of the literature has not brought us any closer to being able to choose the better definition – better according to what criteria, a critical thinker should ask. The literature review has, nonetheless, guided in understanding the concept and has enlightened the direction of the theoretical background of the study, within the context of chemistry education, which is presented in Chapter 3.

3.0 CRITICAL THINKING AS A SCIENCE EDUCATION COMPONENT

Chapter Objectives

From the list of critical thinking skills that were presented in Chapter 2, three are further investigated and attributed to a critical thinking process: investigation and observation in the form of asking questions, analysis in the form of giving explanations, and forming an opinion or making a decision in the form of developing arguments. This chapter focuses on the literature that analyses questions, explanations and arguments in science education and presents them as critical thinking skills directly linked to actions, interactions and tasks that occur in the mid-secondary science classroom. Questions are the initiators in the Socratic Method, from which explanations and arguments are the expected responses. Pedagogically speaking, the study aimed to increase the students' opportunities to have meaningful contributions in the lessons (as will be presented in Chapter 3) to help them articulate their thoughts and develop their ability to participate consistently in the lessons. Later in the chapter, the mechanics of inferring CT from in-class tasks and actions are presented, laying down a frame for the research questions (RQs) that are articulated and analysed in closer detail. The research questions are divided in two categories, RQs concerning the students in-class and the teachers in and outside of the classroom for the data collections. This chapter foreshadows the analysis and discussion of results that will follow in Chapter 5.

3.1 A study of thinking in science education – the case of CASE

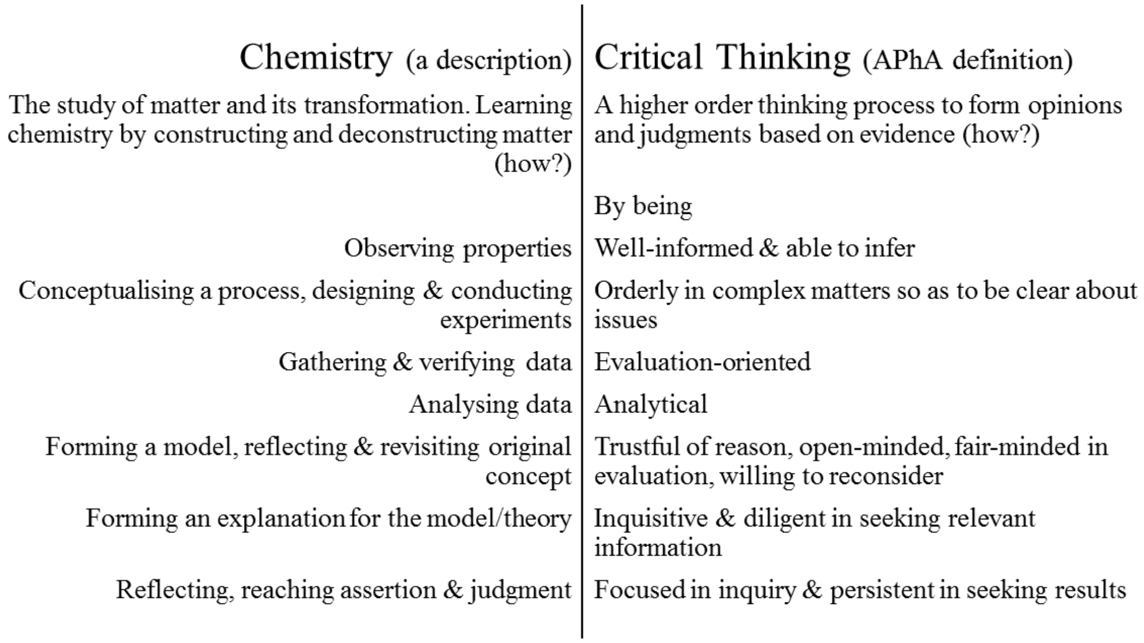
Teaching science at any educational level aims to systematically exercise and improve students' intellectual skills. Understanding science and having a 'scientific inclination' carries a certain prestige that even secondary school students are aware of (Osborne & Collins, 2001). Science education research in England has oftentimes undertaken the task of discovering what may improve both students' attitudes but also attainment in the sciences and emphasis has leaned heavily on promoting scientific thinking habits, implementing strategies to accentuate understanding of scientific investigation and inquiry. The Cognitive Acceleration through Science Education (CASE) project has for several decades used Piaget's developmental theory to aid students accelerate their cognitive skills with the implementation of tasks that advance thinking to achieve “the type of abstract, logical and multivariate thinking which Piaget describes as ‘formal operations’” (Adey, 1999, p. 5).

After the original study in the late 1980s, several schools adopted the model of CASE in teaching formal operational thinking in science education with reported positive results (i.e. Iqbal & Shayer, 2000; Lin, Hu, Adey & Shen, 2003; Mbano, 2003; Endler & Bond, 2008; Oliver, Venville & Adey, 2012). The success of CASE has been that thinking skills of the student participants were checked at three time-points – a pre-test, a post-test and a delayed post-test – and the results showed advanced thinking abilities in both post-tests. Some reports on GCSE English and Maths results for the student participants in CASE showed the possibility that the skills were transferred to other subjects outside of the intended area (Adey, 1999). The CASE study has been based on the developmental stages of the students and how certain skills and mental processes could be accelerated following the psychological tradition. The study related to designing activities that were additional to the curriculum not substituting it as a whole, rather substituting parts of it according to convenient content. The aim of the original study was not necessarily to improve students’ grasp of science education but to improve students’ thinking skills, which in effect would show positive results if students had better understanding of the sciences, and it – and they – did.

3.2 Choosing chemistry education for CT over the other sciences

Chemistry is “the study of the structure and transformation of matter” (Weisberg, et al. 2019), “the study of the nature, properties, and composition of matter, and how these undergo changes” (Russell, 1980). In a teacher educator’s words “chemistry as a science is based upon observations that lead to the development of categories and the identification of patterns, and to ways of making sense of, and understanding, the phenomena” (Taber, 2012, p. viii). Looking in more detail how philosophers and teachers of chemistry describe the nature of chemistry, it is a science with qualitative nature (that is the theory as a brain exercise) and simultaneously tangible quantitative nature, the experiment (Erduran, 2001), “[t]he practice of chemistry is as much a physical activity as a mental exercise” (Bensaude-Vincent, 2009). Educators on the other hand view chemistry in a more practical way that fits the scope of making chemistry relevant to the student and thus helping the student to acquire quality of learning. The duality of the nature of chemistry as a science persists nonetheless “the individual relevance of science education for students encompasses matching the learners' curiosity and interests, providing students with requisite and useful skills for coping with their everyday lives today and in the future, and contributing to the development of intellectual skills" (Eilks and Hofstein, 2015, pp. 5-6). Since it is an experiential science, there is the question why students find it hard to understand chemistry even when they perform experiments. Chemistry is challenging for the majority of the student population in early secondary education (and later). According to student views, chemistry makes better sense when it involves investigation and connects to everyday life (Osborne and Collins, 2010, p. 448). School biology, for example, as the study of the human body, is both interesting and relatable; students learn about their body (Osborne and Collins, 2001, p. 456). School chemistry, however, is not experiential in the same way. Studying the structure and transformation of matter in a microscopic level removes the immediate connection of chemistry to natural phenomena in nature and in everyday life.

Thus, chemistry often seems "incomprehensible, fact-rich but understanding-poor, smelly, and so far removed from the real world of events and pleasures" (Atkins, 2013, back cover) that students do not see the use of learning it. For the experiments, for instance, they have to use agents that they normally do not have access to at their homes, as far as they know. They have to memorise new names and terms and start learning a new language. They have to understand actions that they cannot observe, i.e. interactions of particles in the reactions, or a chemical transformation when an object burns that students need to both understand and explain. Chemical knowledge entails a lot of facts, nomenclature, and classification of substances; it relies on the repeatability of the experiments and measurements for justification ("making, measuring, and modelling," Baird et al., 2006, p.3). To help students learn the abstract content of chemistry we ask them to memorise structures and guide them to observe the changes of matter in experiments. But the learning does not stop there. Students have to further connect the observed changes to robust theoretical principles using modelling and their mind. In essence, for a student to be able to learn chemistry successfully, they have to gather evidence, verify it, analyse it, overview it, find patterns; in general engage in scientific inquiry as it is described in the national English curriculum for Key Stages 3 and 4 (Department for Education, 2014b, pp. 5-6, 11-13 ; Department for Education, 2013b, pp. 4, 8-9). There is a lot of mental effort corresponding to the practical effort that makes up the experiential part. This is what makes chemistry ideal for a study in critical thinking. As per the table below, critical thinking and chemistry require the same mental mechanisms at the same level of robustness.



Chemistry (a description)	Critical Thinking (APhA definition)
The study of matter and its transformation. Learning chemistry by constructing and deconstructing matter (how?)	A higher order thinking process to form opinions and judgments based on evidence (how?)
	By being
Observing properties	Well-informed & able to infer
Conceptualising a process, designing & conducting experiments	Orderly in complex matters so as to be clear about issues
Gathering & verifying data	Evaluation-oriented
Analysing data	Analytical
Forming a model, reflecting & revisiting original concept	Trustful of reason, open-minded, fair-minded in evaluation, willing to reconsider
Forming an explanation for the model/theory	Inquisitive & diligent in seeking relevant information
Reflecting, reaching assertion & judgment	Focused in inquiry & persistent in seeking results

Picture 1: Schematic juxtaposition of descriptors for chemistry and for CT

Both processes are based on learning the methods to gather data, treat the data, analyse, evaluate, model and theorise or form an informed opinion or judgement. The challenge in learning chemistry is therefore learning slowly but steadily to combine processes of action and processes of thought. The challenge for the chemistry teacher, at the other end of the spectrum, is to ensure that in a classroom of students with different approaches to learning everyone manages to follow on building these combinatory processes of action and thought, when each student builds their own individual process. Accepting that “a critical approach to teaching science is less concerned with students accumulating undigested facts and scientific definitions and procedures, than with students learning to think scientifically” (Binker, 1990, p. 512), the study aims to focus on how the process of learning chemistry can enhance students’ critical thinking skills and dispositions as those were described in Chapter 2. To achieve that we borrow the practice described in two pillars of CASE: concrete preparation and bridging (Abey, 1999, p.6) so that we can forge a path for critical thinking to become praxis in the chemistry lessons. Firstly by helping the students to acquire concrete building blocks such as the nomenclature, the classification of chemical compounds, the learning of the periodic table, we engage them is a gradual process of understanding chemical phenomena. Bridging encompasses transferability to other contexts, including students’ daily reality. From the teacher’s perspective chemistry relates to everyday occurring phenomena, i.e. change of the state of matter in cooking, the compound properties of detergents that remove stains (Mortimer and Scott, 2003, p. 15; Eilks and Hofstein, 2013, p. vii)

Looking in the particulars of learning and teaching chemistry, the two components (as mentioned above) are the experiment and the theory. The experiment serves the purpose of introducing authentic chemistry settings for fact retention based on the hands-on experience. The authenticity of the experience draws on chemists' interest in chemistry, which is the experiment, the investigation, finding the answer to the questions 'why and how' (Bensaude-Vincent, 2009). Equally, in chemistry education, experimental procedures are usually meant to provide an impressionable, hands-on experience designed to help students' retention. However, students found experiments repetitive, when they did not escalate to an investigation or reached a conclusion (Osborne and Collins, 2001, p. 452). In contrast, students described favourably those hands-on experiences that were investigative, translated to something they could experience in their life outside the classroom, and were not de facto (Osborne and Collins, 2001, p. 448-9). Using experiments as an engagement practice must, therefore, entail more than a recipe-execution quality. If students do not get the chance to "examine their conceptual understanding and the cognitive processes that produce that understanding [this] cannot lead to learning scientific knowledge of a conceptual nature" (Chin and Brown, 2000, p. 112).

A meaningful experience of experimenting can then lead on to analysis of the data and influence positively the comprehension of the theoretical principles. Many chemical processes are about recognising patterns, being aware of the physical and chemical properties of the elements and compounds, predicting expected products as well as reflecting and seaming knowledge together from different sources. Patterns, similarly to models, are key, because they interpret a wide range of phenomena and are used as predictors to indicate why matter may deviate from the patterns. The Periodic Table is the most prominent example of patterns in chemistry both in its function but also in the story of its conceptualisation. Yet, it can generate "universal antipathy" because of the effort students have to invest in memorising it (Osborne and Collins, 2001, p. 449). Arguably, the Periodic Table makes sense when studied as a pattern. Memorising it is similar to memorising entries from a phonebook; it is pointless. In this example, having students perform experiments to observe elemental behaviours has little result in recognising patterns unless theoretical exercising is also part of the process. In fact it may be best to start with revealing the pattern in theory and moving on to the experiment.

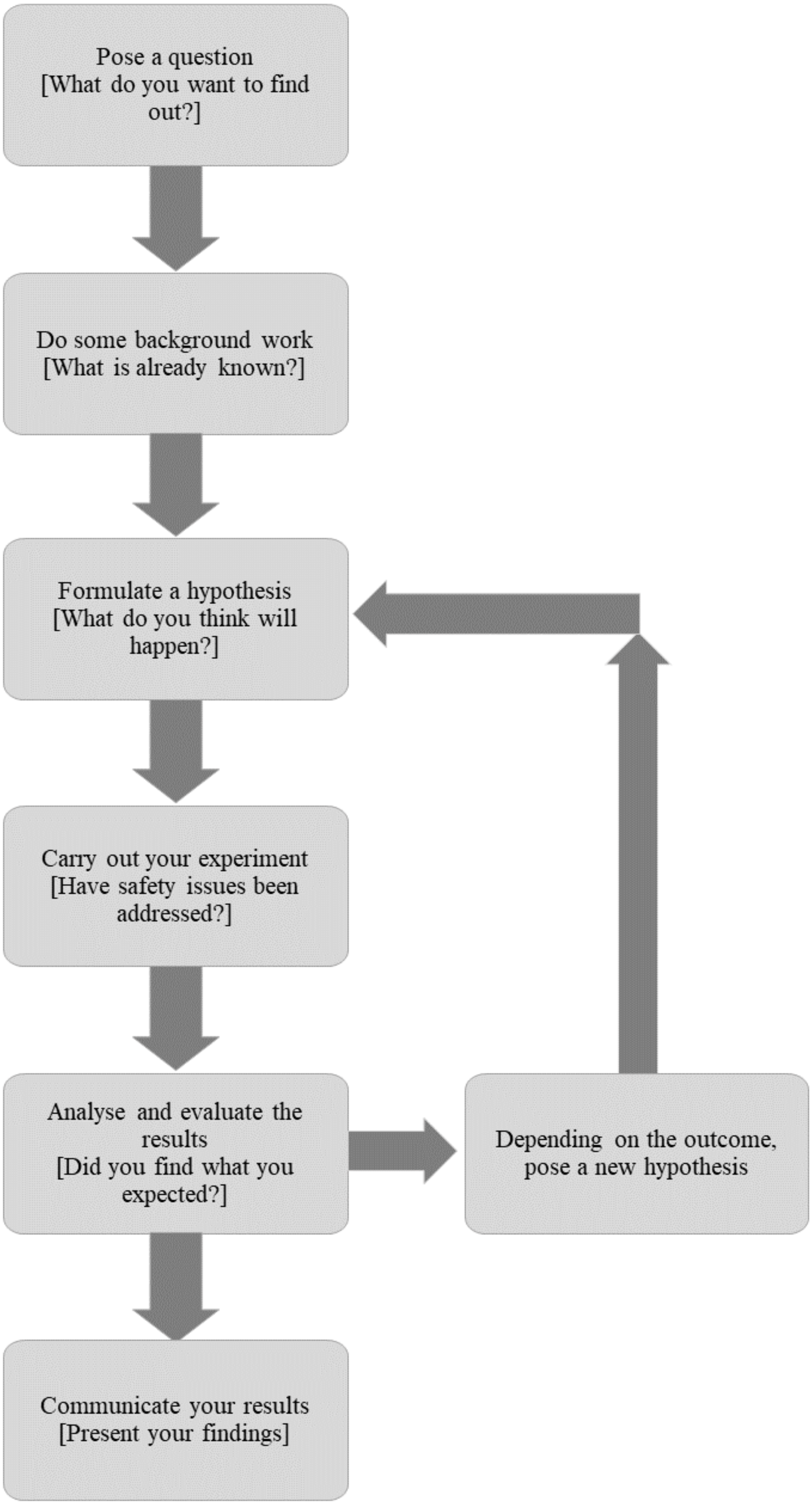
3.2.1 Defining scientific inquiry in science education and in relation to critical thinking

From that mapping in Picture 1, scientific inquiry is a term that can encompass numerous skills and abilities that reflect the rigour, organisation, and consistency of scientific work and display meaningful interactions with science. Before presenting these further, it is important to look into the definition of scientific inquiry and how it resonates with the aim of enhancing critical thinking abilities via learning chemistry.

> Scientific inquiry refers to the diverse ways in which scientists study the natural world and propose explanations based on the evidence derived from their work. Inquiry also refers to the activities of students in which they develop knowledge and understanding of scientific ideas, as well as an understanding of how scientists study the natural world. (National Research Council, 1996, p. 23)

The definition describes the diversity of science, the fact that there are numerous methods by which scientists investigate physical and chemical phenomena and scientific inquiry as defined above is key in science education. “Say ‘science lesson’ to most people and they would probably think of something involving ‘practical work’. … Current curriculum innovation [however] focuses more on explorations and investigation … a more thoughtful approach to science education” (Monk and Dillon, 1995, p.73). Having evidence is paramount and so is curiosity to study the world around us. For students to successfully engage in scientific inquiry, it is important that they accumulate knowledge but also understand the principles on which the scientists base their work, experiments, theories and predictions. However, the point of initiation is suggested to be the question, as a facilitator of investigation (Goldston and Downey, 2012, p. 15, further analysed in Section 3.3) This connects to the study of matter that is chemistry. In the experiment (as mentions in section 3.2), we aim to learn from experience, in the theory we aim to explain what we learn. When students fail to engage in investigation, when teachers fail to present an investigation, scientific inquiry does not ensue.

Looking at the skills and abilities in Picture 1, many of them are inherent in the rationale and practice of science and simultaneously are key for CT development according to the literature. In Picture 2, Wellington and Ireson (2018, p. 179) give schematic representation of what in means to work scientifically in science education (as per the guidelines of the English curriculum in science) that also represents the processes that CT scholars (in Chapter 2) aim for the development of critical thinking. The combination of Pictures 1 and 2 justifies why scientific inquiry – an important, explicit goal in science education – is an essential reference



Picture 2: The scientific method from **Science learning, Science Teaching, 4th Edition*****, (Wellington & Ireson, 2018, p. 179)***

in this study with the objective of practicing CT in the chemistry classroom. It constructs the logical pathways described in the CT development theories, which are also evident in the work of scientists. Scientific inquiry cultivates and improves analytical skills, keenness of observation in an experiment, motivation for inquiry, arguing a point of view, learning the appropriate scientific language and understanding scientific structure and processes (Department for Education, 2013b, p. 4; Department for Education, 2014a, p. 5-6). Interacting with the content in chemistry seems to help students remember it, though it does not guarantee they understand it. Critical thinking and scientific inquiry literatures both propose that unless activities induce thinking and reflection, they promote memorisation rather than active learning. In that light, critical thinking and scientific inquiry in combination should ensure engagement with the chemistry content in the classroom. In the sections that follow, scientific inquiry presents a frame within which critical thinking and learning chemistry merge in meaningful processes that we believe can help develop the former and engage in the latter.

3.3 Questions and questioning in science education and in CT

Questioning is extensively discussed in the CT literature. However, a distinction is made between questioning and the question. For Ennis (1996a), for example, the question was what the individual sought to discover. Yet, questioning is more than the mere question. Questioning relates to the reflective scepticism suggested by McPeck, going beyond the initial point of activation in a question, to include the doubt and uncertainty of what to do next and how to proceed; propelling the thinking process forward until the individual reaches a point of understanding the question, the situation, and the possible solution. Scientific inquiry can be described as the consequence of these labours; towards finding out facts, weeding out inaccurate opinions and substantiating supporting evidence to answering the original question. In the context of the study, the aim was for questions to have the quality of questioning.

Questions have always played a central role in teaching. Over a hundred years ago, Stevens (1912, p. 15), studied the efficiency of questions in the classroom and found that students were the recipients of on average 400 questions per day; but it is the quality of the question, rather than the number asked, which is a crucial delineation of scientific inquiry (NRC, 2000, p. 2). In this light, the question in science is the prompt for observation and investigation and the motive behind offering an explanation and argument in support of a stance. The question alone can commence a series of intellectual and practical actions towards critical thinking.

It is important therefore to examine the questions asked in chemistry lessons and understand their function as a tool for and an indicator of critical thinking. The idea is not novel. It follows in the steps of Socrates who used a chain of questions to guide his students to the discovery of knowledge and fallacy within held beliefs. The intricacies of such an approach lie in the art of asking the right question. For instance, Stevens (1912) went as far as describing a "scientific teacher" as the teacher that took time "to establish ideals, to form habits of thought and action" (p. 4). The "scientific teacher" was not a science specialist, rather they exhibited the ability to ask questions that helped their students to think and reflect. Habits of thought feed into what has been described as critical thinking but they are not devoid of action. For instance, the scientific experiment is an action, inseparable from learning chemistry. Therefore, two crucial questions for this study are to identify which habits of thought are fundamental to shaping students' critical thinking skills; and how these habits are best reinforced, practised and conquered.

The KS3 English curriculum for science expects students to understand "the nature, process and methods of science through different types of science enquiries that help them *to answer scientific questions* about the world around them" (Department for Education, 2013b, p. 2, my italics). Similarly, the KS4 curriculum states that students should be guided to understand and appreciate key achievements of science, one of which is "the quantitative analysis … a central element both of many theories and of *scientific methods of inquiry*… to answer scientific questions about the world around them" (Department for Education, 2014b, p. 3, my italics). The questions asked in any classroom could be grouped together in any number of ways. In this study they are grouped according to the person that generates the question, the quality (referred to in terms of depth), and the purpose. According to these three axes, the categories of interest in this study are: (a) who asks the questions, (b) what the depth of the question is (shallow and deep questions as will be define below) and (c) whether the answer meets the aim of the question.

The first category is pertinent because the overall dynamic in a chemistry classroom is and has historically been that the teacher is the expert, the holder and dispenser of knowledge, the didact who accesses their facts-bank and provides the answers to all the questions (they ask). The expertise of the chemistry teacher is indisputable. Mastering the content is imperative for learning to happen, in contrast to an ignorant teacher being prone to misunderstand and misinterpret scientific facts and procedures and mislead students to misinformation and bad learning. All class participants enter the classroom with this premise already accepted: the teacher knows stuff. Not only that, but also the teacher puts the students to the test via assessment, i.e. questions in a test. For secondary school students who have gone through over half their education career, this dynamic is well-established, so a teacher asking questions is not a new practice, and the expectation of an answer even less so.

The teacher as the questioner creates certain expectations. Specifically, knowing that the teacher knows affects the weight of the question when teacher-generated in comparison to a question that is student-generated. For instance, the question “what happens when an electron approaches an atom?” creates one reaction if it comes from the teacher and another if it comes from a peer. Obviously, the teacher does not ask the question because they do not know the answer. The teacher asks in order to track the progress of understanding or learning. Maskill and de Jesus (1997) claim that being asked a question by the teacher contains an element of threat for students whereas being guided to ask questions among peers “may stimulate thinking and therefore the questions may reveal thinking frameworks” (p. 782). Reviewing the literature in the use of questions in the learning process, Cotton (2001, p. 7) adds that there is no definitive research that relates the attitude of students to the questions they are asked in the classroom, the only result that can be drawn is that students who are able to answer more complicated questions perform better in assessment.

The inference is that there is a differentiation for the student as the questioner. Students asking questions to students inherently has less pressure as an action and therefore, it is expected that the students will be more outspoken, more honest in admitting the extent of their understanding or ignorance and that can potentially influence positively their participation in the chemistry lesson. In a peer environment, the question is an investigation rather than a test. It is a chance for collaboration, retrieval of knowledge and understanding on the subject of charged particles and a collation of this information towards an explanation. Crawford, Krajcik and Marx (1998, p. 704) define peer Q&A as an example of community of learning, which allows for two things to happen: the students are given an authentic science topic to work on and they have the chance to carry the full work on the topic, research it, find and present information independently. This setting also allows students to take ownership of their learning, and engage more actively not only in receiving content but also in understanding it on their own accord. King (1994, p. 340) argues that students who are immersed in the practice of asking one another questions have shown a better grasp of the content. In the studies, students were provided with pre-structures of questions, which they then used in small groups of peers taking turns in asking and answering them. The outcome was that the students were better able to provide information, explanations and connect pieces from different sources more effectively.

Chemistry, in particular, is the type of science within which the results of actions are imminent and obvious. There are dramatic reactions that explode, liquid agents that change colour and so on. These immediately detectible changes are a strong incentive for curiosity and natural wondering of why they have occurred. On the other hand, according to Graesser and Person (1994, p. 105), the average number of questions students ask per hour is three and they do not exceed four. Though this is not a science-specific number, it is obvious that the student-generated questions are far fewer in comparison to the number of questions the teachers ask. This contradicts the ideal of a curiosity-driven subject such as is chemistry.

There are a number of obstacles for students to ask questions, one being the difficulty of students to appreciate the gaps in their understanding (Almeida, 2012; Chin, 2006; Eshach et al., 2014; Graesser and Person, 1994). Another is the fact that like Stevens (1912) pointed out in her research the overwhelming number of questions the teachers ask leaves little time and opportunity for students to ask their questions when they emerge. It therefore follows from common practice that the classroom setting is one that has traditionally fostered a circumstance in which the question falls within the role of the teacher and the answer falls within the contribution of the student. Chin and Brown (2002, p. 522) argue that questions generated by students can signify “a self-directed, reflective learner” and their ability to ask themselves questions helps direct their learning. In this light, a group of students who are able and confident to ask questions in the lesson, not only to the teacher but also to peers would make up a highly competent cohort. It is therefore, desirable that the question-generating balance tips towards the students.

The second category distinguishes questions that are for fact-checking, which in this study are identified as *shallow prompts*, and questions that go beyond fact-checking into recalling and combining information to achieve understanding of a concept and are respectively identified as *deep prompts*. In the literature, there is no unified way of classifying questions in relation to their content. Cotton (2001), distinguished higher and lower cognitive questions; the former being open-end, open to interpretation, inquiry, examination, and the latter being questions that have a right-wrong quality, that are based on remembering a fact or reciting a definition. Dillon (1981) used another type of distinction for higher and lower cognitive questions: the former are opinions and the latter are facts. In general, the classification of questions in either way follows the same logic of shallow and deeper prompts. When a deeper prompt is given (in the form of the question) the students are expected to think before they provide an answer, the question is not straightforward and even if there is a right-wrong quality about the question, it may still require thought, combination of information, structure for verbalising the thought. These questions, by definition, require time, are viewed as open-end questions and students have to make decisions as to what may be the supportive background for an answer (Cotton, 2001).

It is not suggested that the classroom practice relating to depth of questions change drastically. Shallow questions of the yes-no kind serve good purposes as well, they are quick and keep the students alert, they are often asked to bring forth prior knowledge that the students are supposed to know already. The aim of the study however, is different. Quick and easy questions should be of a limited number to give opportunity for more profound, better-structured questions that require more elaborate thought. They also require more time, time that would be taken from another part of the lesson, which is why a reduction in the number of shallow questions is seen as favourable.

The third category is related to the obstacles that need to be overcome for students to recognise questions, ask them or reply to them. When a pause follows a question, the pause may often signal confusion. Students pause because oftentimes they are confused as to what they are expected to say. If they do not know the answer, they wonder if it is something that they should know. In traditional practice, the purpose of question is not speculation or guesswork, rather affirmation of knowledge. However, to activate CT there should be room for what Dewey (1933) called “perplexity,” and by extension speculation. It is also important for students to be able to recognise what type of response would be suitable, be that a definition, an explanation, an argument, a follow-up question for further clarification. Such intricacies that follow posing a question are investigated in the next section and are further analysed in Chapter 5, where the data are presented.

3.4 Explanation in the context of CT in secondary chemistry education

As a scientific field, chemistry entails investigation, gathering, evaluation and presentation of evidence towards conclusions. The inherent level of abstraction of the field necessitates the use of explanations frequently as part of an established practice of engaging in chemistry (Osborne and Collins, 2001; Ogborn et al, 1996; Mortimer and Scott, 2003). In chemistry education, explanation is often the motivation tool to engage with students that have no inclination to a scientific career. The chemistry teacher is familiar with the use of explanation. They know that there may be more than one – often contradicting – explanations for an observed phenomenon creating such tension and reinforcing the abstraction, thus making explanation pivotal in chemistry education (Garcia-Martinez & Serrano Torregrosa, 2015, p. xxi). The chemistry student, on the other hand, has to deal with the emotional aspect of participating in activities they often do not grasp the principles for. Therefore, they are reluctant and to succeed in engaging them the teacher role is partially about creating positive emotional experiences (Bolter et al., 2013, p.70; Mamlok et al., 2015, p. 230). Chemistry teachers are accustomed in producing explanations, but in the context of critical thinking the aim is to motivate student to participate in positive emotional experiences. It is proposed that these positive experiences involve encouraging the students to produce their own explanations.

From the viewpoint of critical thinking, the purpose of being a critical thinker is to establish a belief, well supported with reason and evidence (Ennis, 1996a, p. 2). Explanations in CT consolidate the evidence, data, facts, and formulate an initial belief/opinion. Beyond the science education and CT literature, explanations are also proposed in the practice (syllabus and curriculum). The KS3 and KS4 science curricula, for instance, require students to become competent in understanding *and* explaining scientific information (Department for Education, 2013b, p. 4; 2014b, p. 5). Chemistry is then a conducive field for cultivating students' skills of explaining as it offers opportunities for frequent practice and helps students feel more connected to their science learning experience and therefore better retain the scientific content (McNeill and Krajcik, 2008, pp. 55 and 56).

Teacher explanations stem from the need for the teacher to cover the gap of what students know and what they additionally need to learn. Teacher-generated explanations are well-documented and structured with proper use of scientific language and modelling. Of more interest are the student explanations, which reveal students' knowledge and understanding. To the teacher they also reveal what the students do not know. Though teachers systematically engage in lengthy explanations of phenomena and procedures in chemistry, it is rare for students to do the same. Students, unlike the teachers, do not have enough expertise or experience, nor do they have good command of the scientific language; explanations are an "unfamiliar genre" that they would rather avoid using (Osborne and Collins, 2001, p. 454).

Chin (2006) showed that with proper prompts from their teachers, students produce one- or two-sentence replies that engage them in higher-order thinking by engaging them in "dialogic discourse" (p.1317). Students had the chance to develop and elicit a chain of ideas or a combination of facts for deeper understanding (Chin, 2006). However, opportunities for students to become competent in producing explanations and arguments may be infrequent because of time pressures to cover the content of the lesson or more frequently the choice of teaching practices; with the teacher opting to provide the majority of information and instead ask factual questions that require a single-word or short answer. Cotton (2001) estimated that 60% of the questions asked in the classroom are "lower cognitive questions" (p. 4), prompts that are unlikely to elicit opportunities for thinking and reflecting deeply. Considering when students are more likely to attempt an explanation, these – and arguments as will be analysed in the next section – are usually in response to a stimulus; a task, experiment, exercise, question, or test, actions in the classroom that create and relate to an experience (NRC, 2000; NRC, 2012; Duschl and Osborne, 2002). However, they are often interrupted sentences, incomplete thoughts, key nouns or adjectives witnessing significant points of a process, experiment, or theory. Very often teacher input vastly supports student explanations. To aspire, therefore, to the perfect explanation at the very first attempt, students are set up for failure (Chin, 2006). Encouragement, probing and prompting with more comments or questions or from the teacher – or more rarely peers – can successfully guide students to practice explaining.

In the effort of producing explanations, students have to adjust both their thinking and speech. Explanations may require students "to clarify their thinking, to generate examples, to recognise the need for additional information and to monitor and repair gaps in their knowledge" (Duschl and Osborne, 2002, p. 43) but language of expression is often an obstacle as chemistry uses an idiosyncratic terminology (Duschl and Osborne, 2002). However, when asking ourselves about the purpose of secondary chemistry we are called to decide between educating citizens to make informed decisions or educating future chemists (Hodson, 2009;

Shwartz et al., 2013). Shwartz et al. (2013, p. 48) claim that focusing on the verbal explanation over prioritising symbols learning, the students are more likely to improve in engaging with chemistry. This rigorous process demands more intellectual effort than the recitation of memorised facts. Ogborn et al. (1996) refer to four different types and construct entities for the scientific explanation with the aim to have a solid basis for sustainable explanations. If certain entities are not in place, i.e. the basic building blocks and the element of comparison, the purpose of explaining is vague and the structure of the explanation jeopardised. Clarifying one's thoughts relies heavily on reflection or questioning from another (Osborne and Collins, 2001) and that may lead students to explain what they already know and how this links to new information. Turning explanation to a more personal narrative makes the scientific topic more interesting the students more engaged (Ogborn et al. 1996; Norris et al., 2005).

Explanations are ways for students to externalise their thoughts. Ideally, when students mature in the practice of explaining they also feel compelled to present and explain ideas or reasoning spontaneously without teacher input. Giving explanations enables students to listen to their arguments and improve or rethink their reasoning and engaging in discussions with peers could promote open-mindedness, content retention, negotiation of meaning and finally better understanding (Osborne and Collins, 2001). Attempting to improve students' explanation skills indicates a measure for active critical thinking. In aiming to develop a student explanation platform – as a means of developing CT – it is not realistic to expect student skills to improve by virtue of observing teacher contributions to the platform. Teacher explanations may in fact be a discouraging factor given their professional, expert level. Additionally, the critical thinking theories reviewed in Chapter 2 emphasised that the critical thinker accentuates these skills by constant use and practise. Braaten and Windschitl (2010) argue that the lack of defining the term impedes the growth and development of the skill, which has a domino effect on understanding school science. In that light, a definition and understanding are necessary for the design of study to successfully embed explanation as frequented classroom practice.

McNeill and Krajcik (2008) define explanation as a description of a process/phenomenon combined with evidence (pp. 54-55). Explanations, like the questions, can be shallow or deep, depending on the action (i.e. Chin and Brown, 2000), mechanisms being the most challenging level as they combine observation, investigation, transfer of knowledge and interpretation in different combinations (Woodruff and Meyer, 1997). "Much of the work of explaining in the science classrooms looks like describing, labelling or defining" (Ogborn et al., 1996, p. 14). This necessitates defining explanation in such a way that allows distinguishing a shallow from a deep one. A description, definition or label could easily be mere recitations of a theorem, axiom, etc. meaning there is limited thought process, rather mostly recollection of the correct information. That would be a shallow explanation. Deep explanations are more likely to promote CT as they prompt students to expose the trail of thought. They have an element of sophistication in the thinking, use evidence to establish an understanding for the audience revealing a cause-effect relationship (Chin and Brown, 2000, p. 111). At the same time, they showcase a logical sequence and own understanding of thought and action, "a fact-explaining hypothesis or conclusion that would be justified basically by its ability to explain the facts and the inability to its competitors to do so" (Ennis, 1996a, p. 217). In chemistry, emphasis is on providing a plausible explanation and delving into validations with supporting data. Providing an explanation is a process that needs to be built up via "think[ing] hard" on the subject, "but also get[ting] away from it for a bit," "talk[ing] to others" "be[ing] well-informed" (Ennis, 1996a, p. 218). Considering the benefits of these exercises from the educational point of view, students providing explanations – even false ones – would signify reaching a level of understanding chemistry that makes them feel confident enough to put their understanding into words. In practice, the challenge may be that when it comes to explanations, defining the term is vague and therefore teachers are in doubt of both what it is and how to incorporate it in the classroom practices (Braaten and Windshitl, 2010, p. 640).

3.5 Argument in the context of CT in secondary chemistry education

The literature in science education focuses extensively on different dimensions of the argument. The common factor in scholarly works is the role of the argument in the scientific inquiry, but from that core many different approaches branch out. For instance, argumentation is subject to classroom discourse, how language, or lack of, is used or misused and consequently whether it succeeds or fails to formulate an argument (e.g. Duschl and Osborne, 2002; Mortimer and Scott, 2003). This approach misses to address the issue of using arguments as (part of) a learning practice. Newton et al. (1999), however, described a language competency exercise through a "process of enculturation into science" (p. 556) in the form of collaborative learning in small groups, where dialogue can develop opinions through the exchange of views, evidence and data, in other words arguments. Mortimer and Scott (2003) explored the construction of meaning and how building an argument may emerge via simple questions from peer to peer; questions that seek confirmation of information but also generate uncertainty and therefore reflection (2003, p. 92). Uncertainty was a recurrent mention. It related to the possibility or impossibility of challenging a claim and posited individuals positively towards engaging in further investigations and analyses (Toulmin, 2003, p. 21). Uncertainty, doubt, or opposition were key for the build-up to an argument, not omitting, nonetheless, the risk of performance introversion due to the fear of challenging – or being challenged by – something that seems obvious to everyone else, what Kuhn (1992) called “an acceptance of … falsifiability,” which admittedly is more likely to be observed in students (p. 164).

The argument is a key component in the development of scientific thinking (Erduran et al., 2004) depending on more than the presentation of different – contrasting – perspectives in order to build a cogent scientific argument. Rather in the scientific tradition arguments may be held for a long time and agreement may never be reached (Driver et al., 2000). Much like the explanation, the argument is also an activity that engages students – and scientists – to scientific inquiry with the purpose of equipping them to “justify their claims using appropriate evidence and scientific principles” especially following an explanation (McNeill and Krajcik, 2008, p. 54). To create an environment conducive to argumentation, students need opportunities to develop their own thinking, speak frequently and for longer, search for evidence to support their opinions in a semi-independent manner that can enhance conceptual understanding and skills of investigation (Driver et al., 2000, p. 298-9). Accordingly, arguments are a peer exercise, requiring similar skills and expertise to negotiate conflicting points of view and support an assertion. In such classroom practices, which do not resemble the timeframe and perception of a ‘proper’ lesson, teaching approaches are more elaborate in terms of activities and less so in control of structure (Newton et al., 1999, p. 564-5).

Thus far, the argument is multi-dimensional, and to build an argument requires vigour of thought, filtering and combination of information, structure of evidence/data in a coherent and orderly manner. Naturally, not all arguments are so accurate and thorough. Often, they are more basic, and relate to pure clash of opinions and strongmindedness, a “war that seeks to establish a winner” (Duschl and Osborne, 2002, p.41). Alternatively, the desirable use of an argument is a collaborative exchange of opinions, which aims to promote understanding (Duschl and Osborne, 2002, p.41). Kuhn (2008) goes a step further and substantiates the argument by providing a classification of the supporting evidence: observational correlation, evidential correlation, positive or negative (assertive or rejecting) evidence beyond an opinion, and so on. Toulmin (2003) painstakingly deconstructed the argument to components and dimensions (i.e. the fields in which they belong, the forces that shape them) thus creating a model for building arguments.

According to Siegel (1995), "argumentation … is aimed at the rational resolution of questions, issues and disputes" (p. 162). Kuhn's (2008) proposed definition of the argument is the justification of an assertion, the ability to say how the known became known (p. 681). The production of arguments is a display of strength of thought and competence, the mental development from naïve perceptions to understanding a concept, which then consolidates in words and can be presented to the world. It is also, what makes argumentation such a challenging skill to develop. Arguing a point or explaining a stance greatly improves students' understanding of the content (McNeill and Krajcik, 2008). Learning to construct and deconstruct an argument strengthens the comprehension, interpretation, analysis, critique and evaluation of a stance, and it simultaneously creates room for consideration of the counter-argument, the opposing hypothesis. Given this description, the argument connects scientific theory to applications, and can enable the association of concepts to the experimental data. In chemistry, this translates to theory, which is often abstract, intangible and intellectually challenging, smoothly combining with practice – the experiment. From this combination of theory and practice, a negotiation of understanding, namely the argument, can be distilled.

3.6 The Research Questions

From the analysis of the literature, research regarding science education practices draws on questions in relation to explanations: a question requires a response, but an investigative question requires an explanation to help develop students' understanding of science. Separate to that, there is extensive study of the argument and argumentation as a key concept of scientific inquiry, which in the CASE study is erratically combined to the explanation: understand and explain two sides of an argument (Adey, 1999, p. 25). CASE has successfully activated and motivated thinking as a mode of learning chemistry (and the other sciences) with results manifesting in the way students engaged in the lessons as well as in exam results. In science education, research targeting students' thinking skills and abilities can have a positive effect. Capitalising on these findings, this study aims to use chemistry as an exercise for critical thinking to motivate students engage with chemistry in a meaningful and personal manner and immerse them in the practice of building their content knowledge, while also building a critical thinking device, block by block. Questions, explanations and arguments in congruent parts are employed to create conducive environments, introduce diversity in the practice of a challenging subject, such as chemistry, and keep students' attention and interest heightened.

Chemistry and critical thinking, as studied in the literature, develop in a spiral-like process fuelled by persistence and self-motivation to investigate further. Thus, every turn in the spire takes the person to a deeper, more complicated level of involvement in the exercise, achieving Siegel's (1988) ideal of education for CT. However, the preferable option – education for CT or CT for education – in this study is synergy to maximise the effectiveness of both critical thinking and chemistry education, none being more or less important than the other. In the study, the challenge lies in finding the application/s, the teaching and learning practices that will re-introduce questions, explanations, and arguments to the classroom setting with the aim to boost critical thinking and foster a natural habitual use of them. The initial point for introducing successful applications and practices, is defining the key terms – questions, explanations, arguments – to create the conceptualisation framework and provide the theoretical support for the design of the study (which follows in the next chapter).

Question are the least contentious term, given in the seminal works of Chin and other scholars as interrogative utterances with the purpose of retrieving information, confirmation, or starting an investigation. In this study, the question has a more refined definition as the utterance that initiates or propel an investigation. Given that students already ask questions in the classroom, when trying to verify, fact-check and teachers also ask questions for progress-checking a differentiation is in order: questions of the yes-no-single word quality – shallow as described in previous section – do not promote students' competence in explaining or arguments. This practice lessens opportunities for explanations, short or lengthy, confining the bulk production of them in exam settings. Deep questions or stimuli are more likely to trigger discussions and debates that can explore student assumptions and misconceptions, support or disprove students' original points of view, improve content retention. These are the questions initiating or propelling investigation.

This bridges the question to the explanation but does not define the latter. Echoing McNeill and Krajcik (2008) student explanations are the utterances that provide complete and coherent information on the content and support students' responses with evidence. That moves the practice of explaining away from single-word answers to more sophisticated responses, where the thought path and pattern is partially revealed as well. The study design focused on encouraging explanations that shifted from vague scientific vocabulary referencing to producing an evidence-based, thought-through explanation, theory for a phenomenon. Finally, arguments are those utterances that support an assertion (Kuhn, 2008), the additional information that students may provide when asked to reveal the reasoning behind the assertion, the justification and provision of further evidence to support the formed opinion. Arguments are in a sense similar to explanations in form except there is no classification regarding depth. This component requires depth of thought, understanding and knowledge, so the argument is the ultimate indicator of reflection, critical thinking and deeper grasp of the content.

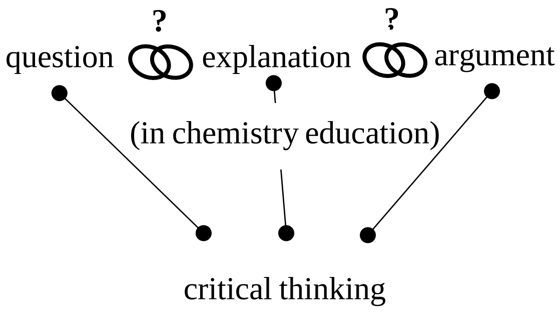
Defining questions, explanations and arguments frames the demonstration of critical thinking. Questions have already been classified to shallow and deep. For instance, when students ask questions that show understanding of a mechanism and the question completes the conceptualisation, this is a deep question. Deep questions from the students are usually quite distinct, because they cannot be answered in a straightforward manner and they cause excitement to the teacher. They are questions that clearly require a number of different actions, mental and/or physical, to get to the answer. Similarly, explanations may be rehearsed citations of definitions; these however, have a completely different impact when they are offered as an explanation supported with data during the design of actions. In the literatures of questions, explanations and arguments, the overview of progression is explicit in becoming more competent a questioner, better at explaining and arguing a point. The critical thinker should be progressing from the simple to the more complex, from the superficial repetition to the profound combination of knowledge and reflection as the CT skills become stronger. Similarly, in chemistry education, the idea of the building blocks uses the same premise, the student chemist must progressively conquer the unknown moving between understanding, experimenting, re-evaluating, and understanding, and so on. Arguments, in this ideal situation, grow naturally as deeper explaining and better understanding turn from opinion to assertion, supported with additional data when challenged. Defining and criterioligising the three components frames the research question and sub questions for this study:

RQ: How can critical thinking be organised and used by teachers in secondary chemistry education using questions, explanations and arguments?

a) What is the relationship between questions, explanations and arguments that allows critical thinking to develop?

b) What are students' attitudes when using questions, explanations and arguments?

Four categories of questions have been identified as contributing to CT: teacher- and student-generated questions, shallow questions and deep questions. Questions from teachers are a norm in classrooms, but students should also be encouraged to ask questions to one another as well as the teacher. Questions should progressively acquire a finer quality (becoming deep questions) to motivate students to reflect on what they know, discuss and debate their points of view. Explanations as a student practice are also inserted in the classroom practice to normalise reflection and presentation of opinion accompanied by evidence. Explanations are also a measurement for CT, as students explain how they reach an understanding of the presented content. Similarly, when assertions are challenged, students should be able to provide further supporting evidence, in the form of arguments, to support opinions and explanations. The focus of the study is the exploration of the links between the three proposed elements and their effective and successful insertion in classroom practices.



4.0 METHODOLOGY

Chapter Objectives

The aim of this study is to help students to develop their critical thinking as a means of understanding chemistry better but also make the chemistry learnt more comprehensible to the students. This chapter presents the methodologies used in the study to turn the theoretical discussions outlined in the previous chapters into a practical application in the classroom; in collaboration with teacher participants, to cultivate a classroom environment that will allow critical thinkers to be developed.

4.1 Methodological approach

The conceptualisation of the study was influenced largely by experiences and observations within the field of science education with a specialised niche in chemistry, due to the specific training as a chemist. Working out the methodology that best suited the study was a challenge because of the largely positivist and experiential training of the research prior to the beginning of the study. Originally an experimental methodology was proposed, which was quickly discarded given the number of independent variables that a classroom reality entailed. Having the experience of teaching and embarking on the experience of researching, there were certain values that were embedded in the study from the outset. One of them was that data would be collected in the classroom, during lessons planned according to the syllabus and following the curriculum. The other important factor informing the study design was that the study should not be an imposition for the teacher participants, rather an aid to embellish existed teaching practices. That brought the focus of methodology to design-based research and ethnography.

Ethnography according to Woods (1991) is ideal for educational research as it brings together the teacher and the researcher in a benign marriage that looks into the needs of the classroom practice and looks to improve them (p. 4), and “the ethnographer aims […] to represent reality” (p. 5). As a research methodology, it is beneficial to the teacher because it allows the researcher to closely observe the classroom and pinpoint moments that illustrate either an issue or a best practice (Woods, 1991, p. 6). Upon reflection on the observation, the teacher can immediately access those moments, analyse them for themselves and intervene to achieve a best result. At the same time, ethnography offers versatility to the research, it is malleable to such an extent that it allows for varied methods of data collection, changes while the study evolves without jeopardising the rigour of the research (Punch and Oancea, 2014, p.156).

Wolcott (1988) defined ethnography as “literally, a picture of the way of life of some identifiable group of people … [that] relate to a generalised description of the lifeway of a socially interacting group” (p. 188). The author argued extensively about the concept of culture in doing ethnographic research, the challenge being that a methodology was born from a practice – anthropology – hence it acquired the nature of both the theory and the practice (Wolcott, 1990, p. 47). In that sense ethnography in education looks into the culture of the school setting in an inquisitive and intrusive manner, the researcher cannot hide their presence or their equipment, the fact that they observe and these observations are later minutely analysed. Ethnography is thus, a beneficial methodology that procures results using semi-defined methods that can be adjusted as per the needs of the population it observes and Wolcott (1990) makes it clear that the results of ethnographic studies have the added benefit of including biases in the outlook of the methodology as methods by offering *interpretations* of the studied culture rather than explanations (p. 50).

At the same time, the design of the study had great influence in the conceptualising it, the design being attempted before the methodology was chosen. Collins (2010) referred specifically to ‘design-experiments’ in education and distilled seven features of that set them apart from more traditional experimental approaches:

1. Messy situations – real research happening in the classroom
2. Multiple dependent variables in the research
3. Characterising a situation
4. Flexible design that allows for revision
5. Social interaction
6. Developing a profile instead of stating a hypothesis
7. The notion of a participant as a collaborator in the design (Collins, 2010, p. 367).

The methodology for the study was mainly ethnographic. It was actioned in chemistry classrooms with varied participating groups that had fewer characteristics in common than setting them apart. The common factors were the content of the syllabus and the curriculum. There were different age groups of participants and as is well-known to teachers, each cohort had a particular idiosyncrasy. The teacher participants viewed the researcher as a consultant who could participate in the reality she was there to observe. Ethnography as a methodology offered further flexibility for the design to develop according to the emerging needs and responses of the participants to the study. Given the ‘messiness’ of the classroom environment, Collins’s (2010) proposed design allowed for the collection of qualitative and quantitative data from the observed interactions of the participants and contributions from both teacher and student participants.

4.1.1 Study methods

In designing the study, a positivistic tool, an observation grid was chosen to record observations in the natural learning environment of a school classroom. Acknowledging that an observation tool has certain insurmountable limitations, it was, however, necessary for better focus, for discerning relevant instances, for recording the overall changes of a group over a period of time as the graphs will show in Chapter 5. Such a method for data collection is pre-designed to fit the purpose of the study, because in using the designed tool, the observer has trained themselves to observe the instances that inform the study, usually against a list of actions or codes. Acknowledging the inherent bias of the observation grid, the observer may be oblivious or indifferent to instances in the classroom that seem irrelevant to the purpose of the study. In this particular study, for instance, a conversation between students and teacher about another lesson they have in common would be irrelevant to the purpose of the study and therefore would be recorded as irrelevant conversation with little further exploration.

Observation grids have the additional risk and benefit of grouping behaviours together, thematising them. From the limitation point of view, in classrooms full of activity with numerous participants and several activities happening simultaneously a single observer can hardly capture the exact activities of twenty or more individuals in the classroom at every instance. There are also the unobservable elements such as the mood the participants come into the classroom with, the presence of strangers (i.e. an observer), the pressure or nervousness an observation pattern may cause (Richards and Farrell, 2011, p. 91). On the other hand, thematising the behaviours allows for the detection of patterns, the quick recognition of best and weak practices and therefore adjustments can be implemented as the study evolves. Though ethnography in its pure form wants the observer to be unobtrusive to the culture they study, a design experiment leaves room for an observer-participant as well as a participant actively shaping the research.

The choice of methods was guided from the pilot observations that informed about the setting and focused on those classroom instances that revealed potential CT-enriched practices. Missed opportunities were also identified which were translated into desirable context that shaped the classroom practice for CT. Successful instances, on the other hand, were recorded in detail to create a bank of suggestions and create similar circumstances in the main study. The quantifiable aspect aimed at a macroscopic point of view whereas the qualitative aspect offered a rather microscopic analysis. As will be shown in Chapter 5, the quantifiable data were complemented with qualitative observations, interactions of participants, reflective notes and interviews. Ethnography made it possible to conceptualise how these diverse sets of data could be linked in the analysis and the design experiment accounted for the flexibility within the study setting without imposing on the value of cultural aspect. It was a study looking in the cultures that emerged in the chemistry classroom with the intention to analyse them and influence them to become CT-oriented.

In a domino-like effect, the methods ought to allow the participants to interact with the research, to effectively influence the cultures. Therefore, an informal protocol of communication was established with the teacher and student participants that ensured that teachers had control of their teaching and had the opportunity to opt in or out of using suggested practices. This led to a series of semi-structured interviews with teachers for different purposes at different times. The purpose of the communication at early stages, before the observations started, was the introduction of the study and the idea of critical thinking to the teacher participants. Later communications with the teacher participants were a means of recording teachers' reflections and feedback on the progress of the study, the success of suggested practices and as guidance for future lessons. The methods employed for the data collection are detailed in section 4.3, once the focus and lesson content of the study had been decided upon. The platform of communication with the students was assigning them the responsibility of recording their interactions in the classrooms during the study. Further to that, one of the groups participated in semi-structured reflective interviews regarding their experiences in chemistry.

4.1.2 Design of the study

The study was designed to happen in the natural setting for education, namely schools and focused on cohorts of Year 9 and Year 10 students and their chemistry teachers from two different schools. The planning and organisation of the observations were recorded using two methods: the use of the observation sheets and video or audio recordings of the lessons.

The design of the study was firmly based on the student-student, and the student-teacher interactions from the pilot observations (Section 4.2.1, Figure 1). During the pilot, the interactions were spontaneous, the teachers followed their chosen lesson plan with clear goals on content, aims of learning and awareness of the level of competency they wanted their students to achieve. This left the thinking component in chemistry unattended. Despite the lack of attention from the teachers, the students would often become bright-eyed with a personal discovery, or a newly-founded understanding of a theory, upon which they would ask advice from the teacher. Usually, the teacher response was to point out the mistakes in the students' work without seeking the reasons why their students were asking the questions. These were the interactions that guided to the structure of the study; driven by the teachers' response, their apparent lack of awareness that good thinking skills were not reinforced by these responses, instead an explorative response from the teacher could have positive impact for critical thinking for the student. These unnoticed – and therefore not encouraged – instances of students showing ability for critical thinking could be transformed by allowing more time for students to come to conclusions on their own.

The aim of the study was to co-operate with teachers and adjust the regular teaching practices for more CT opportunities in the chemistry classroom, via explanations or observations, for instance. That required an implementation of a scheme or lesson plans that were made up of activities to exercise students' critical thinking as often as possible. However, the firm base for the study was a collaboration with the teachers and the use of practices that the teachers felt comfortable with and could use after the end of the study. On that premise a teacher-focused implementation that required the teacher to use entirely new teaching methods was not likely to have long-term effects, especially when working with experienced teachers. On the other hand, the student participation was of equal important. The studies would be incomplete if the reactions of students to the implementation were not captured and analysed. With these principles in view, specific lesson designs were considered but rejected. Instead, suggestions of activities for training in specific critical skills were offered in teacher-researcher communications beforehand. The decision of what activity best suited each teacher and their lesson lay entirely with the teachers.

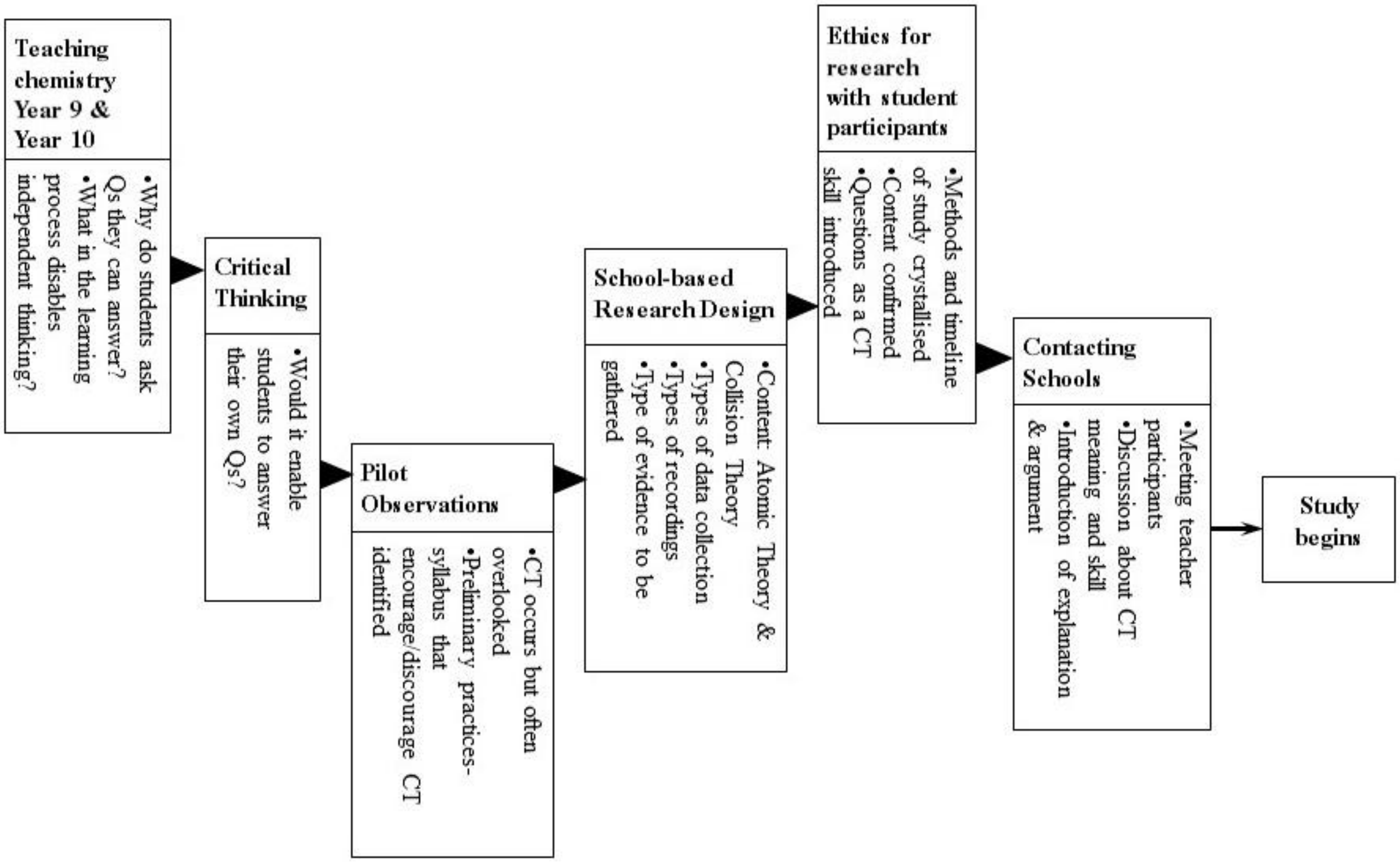


Figure 1: Conceptualisation of the design for the study

The question that the teachers and researcher were at work to discover was how a critical thinker comes to think this way, specifically what elements in chemistry education can encourage critical thinking. Meetings with the teachers before commencing the observations served to frame the study and negotiate meanings for key terms as well as setting the type of input that was to be offered and expected. The study was originally designed to have a single approach for all participating cohorts and teachers. The same philosophy was applied in conceptualising the intervention, so it was sensible to have the same designs of the same rhythm but different content. However, discussing the content of chemistry with the teacher participants of different Years and schools led to a differentiation of designs. Eventually, three different designs were used that differed in the length of intervention per cohort and the pattern of visits to the schools (see Figures 1, 2, and 3 in Section 4.3.2). One study was designed for the Year 9 cohorts with a differentiation per cohort and another for the Year 10 cohort. The studies still shared the same philosophical principles but differed in application of the intervention. The CT skills that were under observation remained the same for all cohorts. Figure 2 is a schematic representation of what was included in the studies' design.

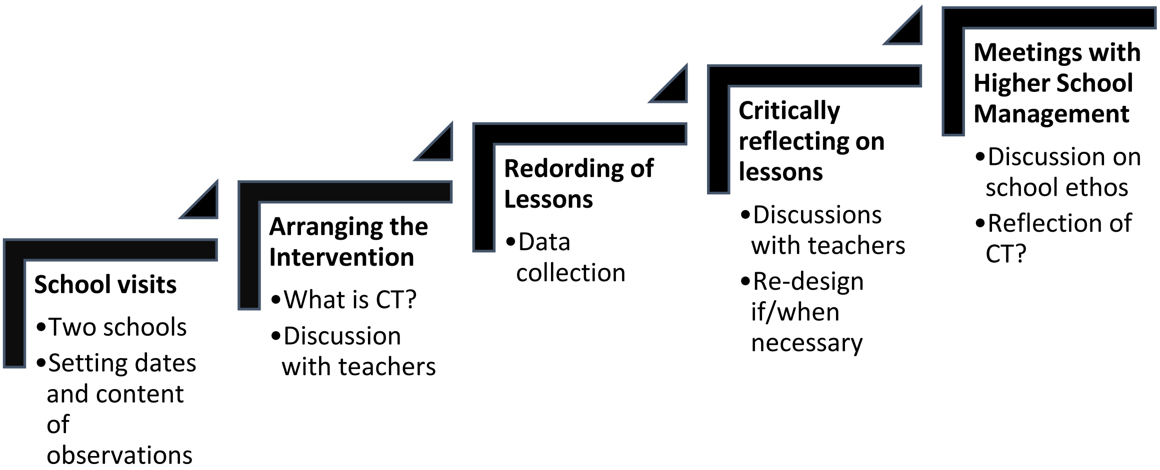


Figure 2: Design of Studies

4.2 An analysis of the Year 9 and Year 10 Chemistry Syllabi

An analysis of the syllabi is important to highlight the areas of content that offer the most opportunities for an enriched critical thinking practice.

4.2.1 Pilot Observations

In order for the design of the research to be conceptualised and the data collection and analysis to be coherent it was necessary that pilot observations and pilot discussions with chemistry teachers of Year 9 and Year 10 cohorts be undertaken before the data collection started. A school in the wider Birmingham area was contacted and a chemistry teacher, who will be called Tom, agreed to meet and share his experience as a chemistry teacher as well as allow visits of an observer in his classes. He also informed his colleagues in the science department of the visits and research and they were equally welcoming to the idea of their lessons being observed. Discussions only involved Tom and they were not recorded in any way other than reflection notes and a reflection log of ideas, potentials and second-hand experience. Tom had more than ten years of experience teaching chemistry and was a chemist. As an experienced teacher, he had gone through many curriculum and policy changes and he was able to present the science education syllabus in terms of lesson planning, and lesson preparations. He could explain the expectations and aims that the team of teachers set for the cohorts of students in his school. The detailed lesson planning Tom offered and the expressive aims per lesson provided an overview of the syllabus, insight of how the curriculum was practically applied and where in the syllabus there were promising areas for a CT intervention.

These pilot visits put into perspective the content material that was currently taught. For instance, according to the curriculum and syllabus for science in England (Department for Education and Skills, 2004, pp. 76-77) the Year 9 chemistry content is the Periodic Table without specifying teaching about the atom and the atomic theory. Year 10 content in chemistry focuses on reactions and materials' changes, again with no formal teaching of the atomic theory (Department for Education and Skills, 2004, p. 185). Tom, being a trained chemist, thought that the atomic theory is an important prerequisite, because it is essential in understanding the periodic table, the structure of elements and compounds, the movement of electrons and a number of other topics included in school chemistry. In Harlen's report (2010, preface) understanding the atom and how it relates to every existence in the world is cited *first* in the list of ten essentially fundamental “big ideas” to know about science. Tom, an experienced practicing chemistry teacher, strongly agreed that the atomic theory should be the “big idea” for chemistry, as in his logic it is more challenging for middle secondary school students to understand materials in their macroscopic dimension if they do not know about the microscopic, fundamental building block, the atom.

Tom shared his Year 9 and Year 10 lesson plans that framed the expectations of teaching chemistry over a year, but also the expected outcomes per lesson. Each lesson plan included a statement of specific aims, which were specified and explicitly presented to the students at the beginning and at the end of the lesson. This way of starting and ending a chemistry lesson was the first instance that I highlighted in my notes. From the study perspective, I recognised that, on one hand, this enabled awareness of the teaching aims for the teacher and the learning aims for the students but it also dictated what each student’s outcome of learning should be for the lesson. The practice begged the question of the true value in stating these aims as they seemed to deprive students of the opportunity to explore what the lesson was about, to independently link the new information to prior knowledge, to follow a more creative way of discovery. Stated learning aims, on one hand, left students who had not achieved the said aims, disappointed or disinterested because they had failed. On the other hand, this practice potentially provided opportunities of laziness and distraction for the more able students, if they achieved the aims quickly enough. In either of these possibilities, there was little opportunity for perplexity to generate reflection and set in motion a CT process. The discussions with Tom and the observations in Tom’s school guided the conceptualisation of the design for the study. The design is explored in section 4.4 and looks at critical thinking as a means to build confidence in learning chemistry, and create an environment that fosters curiosity and further exploration towards discovery and theory formation, all of which require a number of critical thinking skills.

Observations of Tom and his colleagues in their respective groups indicated a noticeable imbalance between the frequency of questions that were asked to and by the students. This further led to an examination of the type of questions asked and the response obtained. For instance, when teacher questions required a single-word answer, then they were classed as shallow, whereas if they required an explanation, some thought and recollection, they were thought as deeper (shallow and deep are the chosen terms of characterisation within the study as per Section 3.3).

Questions from students to the teachers as critical thinking opportunities were also scrutinised, to see if they were questions that required confirmations or explanations and the variety of ways teachers responded to students' questions. Students appeared to acknowledge their teachers as experts, and so they often asked questions with the intention to take a short cut in order to avoid working towards the answer themselves. This focused the study on an examination of the types of questions asked by students and the type of responses provided by their teachers. Though the study was originally targeted towards students and certain factors that affect their attitude towards chemistry, the observation of the classroom dynamic clearly emphasised the need for the study to have both student- and teacher-participants.

Prior to meeting Tom, it was important that there was familiarity with the content of school chemistry for Year 9 and Year 10. The curriculum had been analysed to discover whether a study in CT was at all relevant for middle-school student (Section 3.1), and it needed to be complemented by knowing what was being taught. The study of the Year 9 chemistry textbooks proposed by the Department for Education was informative of content and layout of the books. The textbook source consisted of a student book and a teacher book. Its purpose was to suggest a way for the teacher to navigate through the syllabus but teachers were not obliged to use these books. The student book was broken down to units and the units were further broken down to two-page sections that had information in text bubbles and note style. The pages were filled with a lot of pictures and colour, which made the book look user-friendly, but at the same time offered poor quality of support in terms of content. There was little procedural structure and the book's layout did not help focus on what students were supposed to learn and how. It also included little in way of exercises and chemical problems. Considering that chemistry is a practical science with a lot of mathematical modelling and algebraic equations of charges and mass, a textbook that does not include such exercises and does not provide enough examples of solving problems or exercises for practice, thus leaving a gap in chemistry learning.

In practice, Tom clarified that he hardly ever used the textbook and, in fact, the textbook was more of a suggestion than an actual study guide. The teachers' book contained the same information as the students' book but also included comments, instructions and further chemistry-related information that the teacher could *say* to the students. This information did not exist in the student textbook so the students had no access to it outside of school. The teacher book looked more appropriate for students to understand the chemistry lesson of the day. Discussing this with Tom, he explained that students were not expected to learn from the textbook and the use of the textbook was rare. Most of the lesson according to Tom was based on slides that each teacher prepared for his/her lesson, activities that were designed to reinforce the content of the day's lesson, science education videos that the government or other science communication agents had created for school use or science communication functions. The syllabus also included a number of practical lessons that were based on the demonstration or performance of experiments for hands-on experience. Those were either purely focused on an experiment, as a follow-up to a previous lesson or they were theoretical and practical, where half the lessons were experiment-based and the other half were theory-building related to the experiment. Tom shared the materials that he used to prepare his lessons. These were seven old textbooks – not including the textbook currently in circulation – and his lesson plans per lesson prepared by either him or his colleagues and readjusted to fit the new syllabus or cohort. There were several chemistry videos and a bank of written activities that were used. The videos were relative to the content of the lesson and the activities were for either in-classroom practice or homework. He explained that all these materials would be subject to change over the year according to the strengths and weaknesses of the cohort.

To summarise, observing the teaching practices in Tom's school and engaging in extensive discussions with Tom about the curriculum, the syllabus, our individual views about fundamental chemistry content, I had the opportunity to familiarise myself with the practices of chemistry education in England, the intricacies that the curriculum imposed in terms of content and the way teachers handled those. This experience formed the outline of the design of the study. Specifically, from these visits I was first able to decide the content of the Year 9 and Year 10 syllabus that could serve the purpose of critical thinking. These were the Atomic Theory in Year 9 and the experiment-heavy topic of Collision Theory for Year 10. The second key element that entered the conceptualisation of the design was the question. When students engaged in investigations with the guidance of their teachers, student theories would often be corrected in a dismissive manner with the teacher offering the correct answer without discussing, explaining or arguing the incorrect ones. This helped me visualise the type of teaching practices that would enhance critical thinking as well as the types of learning practices that would allow students to express themselves. In my mind, if the teacher questions had a rhetorical character, in the sense that the students were expected to use their own thinking devices to provide the answer, critical thinking had to be involved bridging the practical to the theoretical as explained in Chapter 3. Each thought from the observations in Tom's school propelled to the next level of observation, i.e. from the number of teacher questions, I moved to the quality of teacher questions (shallow or deep), to the quality of student questions, to the student responses, to types of student work and class participation, to the need to augment student explanations. Arguments were not observed but taking the conceptualisation of the connection of questions and explanations to the occurrence of CT in the classroom, I thought if the teachers were encouraged to challenge their students by questioning thinking process, students would argue to not only explain but convince with their theorising, taking the critical thought process further.

4.2.2 Year 9 Syllabus

The syllabus for Year 9 commences with an examination of historical atomic theories, followed by the structure of the periodic table and the recognition of patterns, which feeds into atomic structure and the properties of Groups 1 and 7 of the periodic table. These lead on to the consideration of reactions according to electron exchange and, eventually, the microscopic and macroscopic impact of such exchanges environmentally and astronomically.

From these topics, the content relating to the periodic table, metals and their reactivity and the atomic model and theory were considered appropriate for the implementation of the study. The topics were chosen based on the pilot observations and conclusions that this content is crucial for building a foundational understanding of chemistry. Teachers expressed the need for students to have a grasp of the basic understanding of how chemistry developed differently to the other sciences. Similarly, Harlen’s (2010) report, *Principles and Big Ideas of Science Education* included the understanding of the atom in its list of Big Ideas, through which students can familiarise themselves with the fundamental concepts of science and develop an inquiry-based thinking structure that will allow them to grow into mature decision-making citizens. In addition, these particular topics require students to use specific skills in order to understand the content. For example, the syllabus expected the atomic model to be taught via an historical exploration of earlier models. Though history of chemistry is often included in the textbooks, it is not usually the focus of teaching, because knowing past, flawed, models does not contribute to the end goal of successful exams in current science. However, examining the flawed models chronologically was a topic of choice for Year 9 from the syllabus, because it illustrated the way the models developed; building on one another, expanding previous knowledge, reviewing and reflecting previous evidence. Therefore, such a chronological approach could be used as a structured process for the development of thought, during which the use of models as static, fact-based illustrations of universal truths could be challenged and are better understood as products of thought, evaluation, reconsideration, and often based on observations of outlying data, about which scientists are looking for explanations.

Similarly, the study of the periodic table would enhance students' skills of observation, discussion and possibly debate while negotiating meaning; since the curriculum states that students should be able to "interpret observations and data, including identifying patterns and using observations, measurements and data to draw conclusions" (Department for Education, 2013, p. 4). Recognising patterns in the periodic table would allow students to undertake progressively more detailed observations of features shared from element to element, but also the accumulation of content, longer exposure to the basic information and therefore a better chance for practice and gaining experience, which is necessary at a primary stage (Dewey, 1933). Such observations would also enhance understanding of how features are influenced by size of the atom, for instance, and training this skill can possibly lead to predictions of features for other elements. I based the concept of looking into student and teacher interactions on this particular visualisation because it was both interesting and challenging to observe teacher give a CT-rich exercise to the students and then minimise the CT opportunities by not engaging students in explanations of their thought process and argumentation of their theories.

4.2.3 Year 10 Syllabus

The syllabus for Year 10 chemistry is an extension and expansion of the syllabus for Year 9. These two years seem to be designed as a continuum with Year 9 topics inserting the students in a more scientific content and way of thinking and the Year 10 moving further in scientific inquiry, experiment and methods of analysis and evaluation, which are designed to commence the studying for GCSE exams. Year 10 chemistry starts with the atom and the periodic table, conservation of mass, amounts of substance and volume of gases, it continues with reactivity series, types of bonding, reactions and reaction equilibria and then goes on to explore reactions further in terms of types of reactions, rates of reaction. As focus in the most recent curriculum there is specific on environmental issues, the Year 10 syllabus also includes a unit devoted to environmental chemistry, the chemistry related to industries and the impact the chemical changes and reactions have in everyday life. Rate of reactions was chosen as the focus for the Year 10 study because this unit fit very well to the objectives of the study.

The different schools involved in the study taught rates of reaction using a number of practical activities that could be done in the school lab. From the content, the factors that influence the rates of reactions are fairly diverse which provided opportunities for teachers to organise series of experiments wherein students could observe the way different factors speed up or slow down a reaction. Keeping a record of these observations over the series of experiments would, ideally, lead students to recognise patterns and draw conclusions on how reactions progress when affected by the presence or lack of these factors, and environmental influences. It was also hoped that this would lead students to hypothesise about the influence of the observed factors and predict what may happen for factors that were not used in the experiments. These features resonate with the objectives of a skills-based study on critical thinking. In the study, an introduced diversified classroom environment would activate students' observation skills, and the recording of the findings could propel conclusions.

4.3 Data Collection Methods

Action research methods and collaborative action research principles were used for both the quantitative and the qualitative parts of the study. Classroom observations were used to obtain quantitative data as well as providing qualitative information through the researcher's reflective notes on the lessons observed. Interviews were also recorded to capture teachers' views and a short questionnaire was given to Year10 students in an attempt to capture their opinions and reflections on learning chemistry.

4.3.1 Action Research

The methods used in the study were influenced by the principles of action research. Klein (2012, p. 4) described action research giving specific characteristics: a review of current practices, the development of a plan to change a narrowing and focussed aspect of practice and the organisation of research questions and planning of actions to collect data to assess the impact of the change of practice. Similarly, Provenzo's description of action research is:

> Action research involves four areas: (1) identifying a focus of research, (2) the collection of data, (3) the analysis and interpretation of what is found, and (4) the development of an action plan based on one's research. Action research can include both qualitative and quantitative data collection. It does require, however, that teachers become active observers of what they teach and how their students learn (Provenzo, 2009, p. 13).

Action research is a useful method for undertaking research in the natural environment of the occurring phenomenon because the planned implementation follows a cyclical pattern of designing, applying, evaluating, and re-designing (Klein, 2012, p. 4). Action research develops in a spiral fashion that is when the results of the implementation reach a point of saturation the cycle reaches an end, the data are reviewed and the research plan is adjusted to new aims. As a result, actions that had brought no results were removed from the original plan and new actions were planned. Similarly, actions that produced results were also reviewed by the researcher or the team of teacher and researcher to come to better understandings of the mechanics and how those might be more favourable to meeting the study's aims. This research process was dynamic and changeable, and in synchronisation with the philosophy of reflection on teaching practices, critical evaluation and re-adjustment of these practices underlying this.

Action research was considered a favourable choice of design for the study because of the flexibility it offered in terms of design. On one hand, the inexperience of the researcher and on the other, the desire of the teacher participants to be actively engaged in the development of the intervention plans, enabled a dialogical dimension to be included in the design. The principle of collaborative action research where the participants also contribute to the development of the design of the research was incorporated at an early stage. In communications with the teachers the approach gave all involved the freedom to discuss and reflect on current practices, decide whether or not they wished to try suggested new practices, such as asking students to undertake the video recordings of lessons. As Sagor (1993, p. 9) claimed to simply reflect on practice is limited, and reaches a stalemate for a teacher with little time to perform all the duties the job encompasses. On the other hand, collaborating with a colleague, or a researcher required a different level of commitment. Of course, these are not novel approaches, as teachers may often exchange views about teaching practice. Rather, the study normalised the exchange and frequency of ideas in the communication between research and practice. Torre et al. (2015) have also presented the benefits of Participatory Action Research (PAR) from a democratic and historical viewpoint and pointed out that PAR opens the channels of communication between research and practice so that one informs and educates the other and it is to the benefit of the study that lessons were designed in cooperation using a joined decision-making process.

Consequently, the three groups did not have the same research cycles. Specifically, Group 1, (School 1 – Year 9) had a weekly cycle of action research, driven by the need to re-adjust the observation codes and because of fluctuating level of comfort the teacher participant felt as the intervention progressed. This teacher, Hannah, was a very active participant, who completely immersed herself in the study. She was very outspoken about what she was comfortable doing and what she was not comfortable doing and yet she tried out practices with which she was neither familiar nor comfortable with, because "this is why we are doing this, isn't it?" (from interview with Hannah). The intervention with Group 1 lasted seven weeks overall (the longest of the three interventions), thus allowing a subtle change in the teaching practices to take place and a longer exposure of students to reflective discussions in the class both with peers and the teacher. It also allowed for closer and more frequent researcher-teacher communication and collaboration inside and outside the class. Hence, beyond the establishment of core ideas and aims, which happened early on and formed an overall protocol for action, the approach was not strictly structured, rather the teacher discussed creative practices she intended to use before and after the lessons. The teaching method or practice used for each lesson was suggested by the researcher, however, the choice of practice was upon the teacher. Hannah often followed the research suggestions. When she did not, she modified a suggestion to a practice based on the same principle but feeling more familiar and manageable to her.

Action research was not applied for Group 2 (School 2 – Year 9). The teacher, Samantha, had a very different approach to Hannah. Her teaching practices allowed her to have absolute control of what was happening in her classroom and she did not feel comfortable trying new approaches, since her experience was proof that her methods worked. She was confident in the knowledge that the school management was happy with her performance and the performance of her students and therefore, she was not willing to change her teaching practice. Samantha agreed to participate with her Year 9 cohort as a control group and to offer her views on critical thinking as a tool to be used in the chemistry classroom.

Finally, Group 3 (School 1 – Year 10) had two distinct cycles of intervention, each of which lasted two weeks. For the first cycle, the two weeks made up a complete cycle, because the intervention for Group 3 was based on a series of experiments for the specific theoretical field of Rate of Reaction (as mentioned in Section 4.2.3). The first week consisted of theory building and the second week of experiments to specifically generate Collision Theory and verify it with results. Once that cycle was over a second cycle was organised with the collaboration of the teacher, Harry, for later in the year when Group 3 would be performing those experiments again during their coursework.

4.3.2 Classroom observations

The conceptualisation of the observations is placed in the tradition of scientific inquiry and followed a process that aimed to record and explain measurable data in a social setting, which for this study is the chemistry classroom. Hilberg et al. (2004, p. 2) gave a list of the elements that should be considered when developing a design. Some of these were: the purpose of observation, the definitions of the observed behaviours, the unit of time for the recorded observations, the observation schedule or frequency, the recording tool and method of analysis. The recorded observations can then become measures of actions and behaviours in the classroom and allow for their systematic analysis: for example, for this study, the counting of how many times an action occurred and the impact in the observed learning and teaching environment. In accordance with Hilberg's et al. list, timelines were drawn for the observations for the study per cohort of participants (Figures 3, 4 and 5).

Quantitative approaches for classroom observations draw mainly on a positivist tradition and rely on measurement, the coding of actions, and a more rigorous recording of interactions and occurrences, whereas a qualitative methods "concentrate on the significance, meaning, impact, individual or collective interpretation of events" (Wragg, 2002, p. 10). Convincingly, O' Leary (2013, pp. 48-49) presents qualitative and quantitative approaches as the two ends of a continuum, wherein qualitative observations are of an explorative or interpretive character and quantitative observations are focused on the systematic measurement and classification of data and resonates with the study's use of reflective notes as a positivistic observation tool.

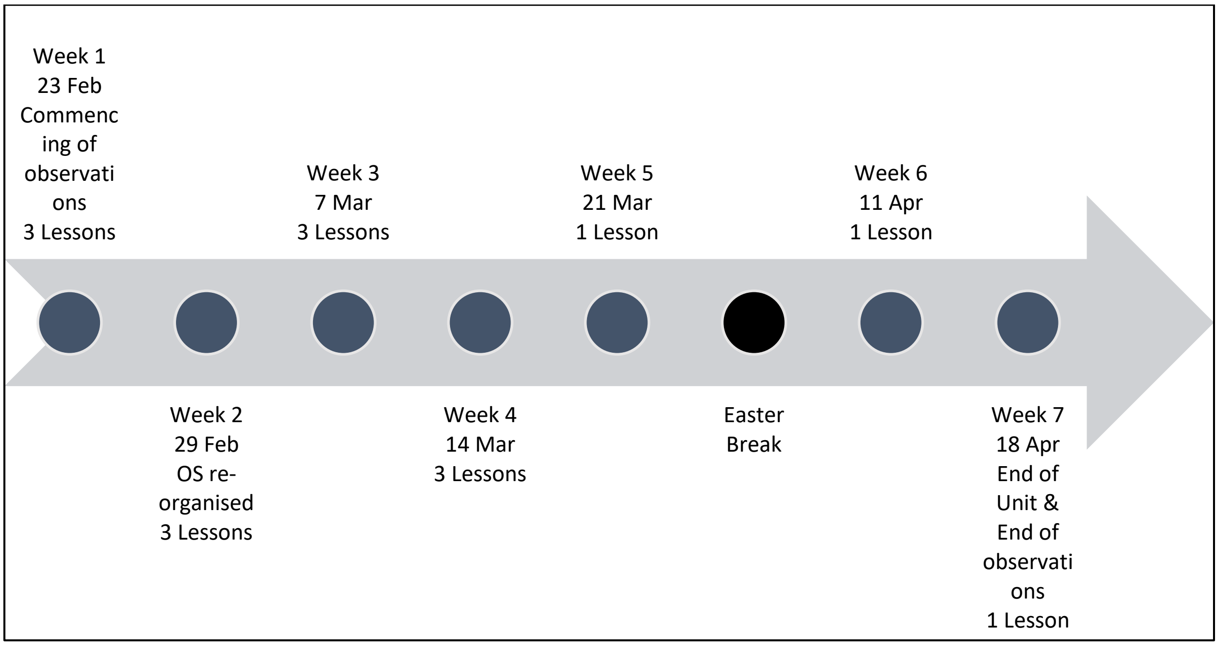


Figure 3: Group 1, Observations timeline

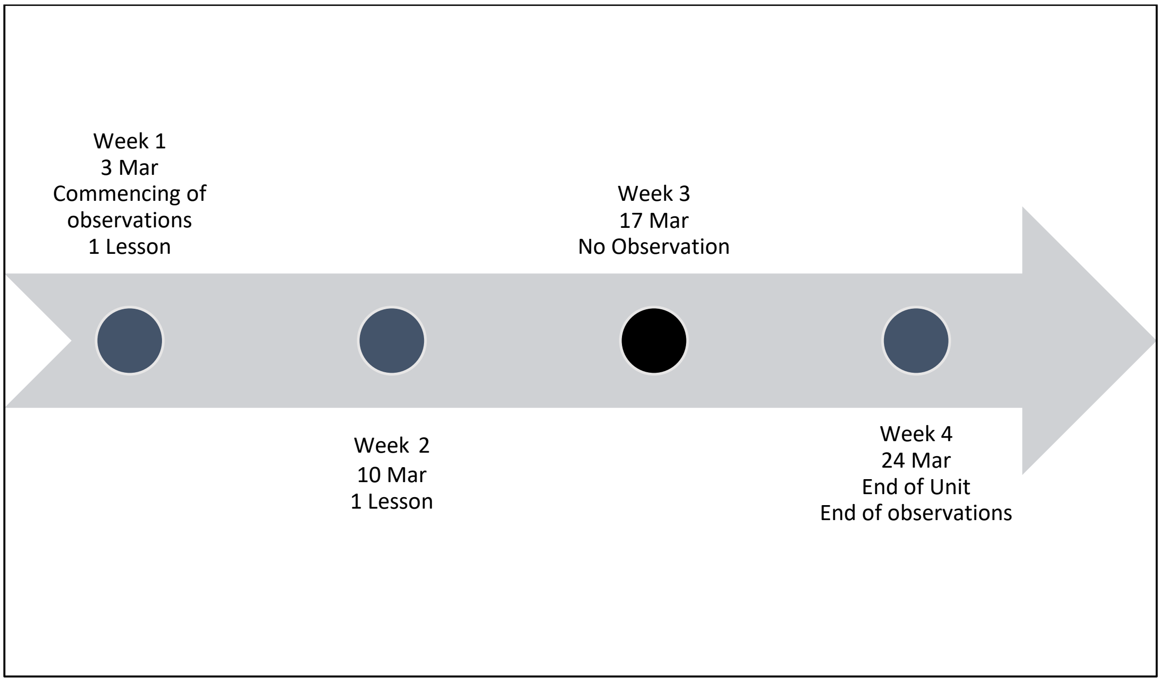


Figure 4: Group 2, Observation timeline

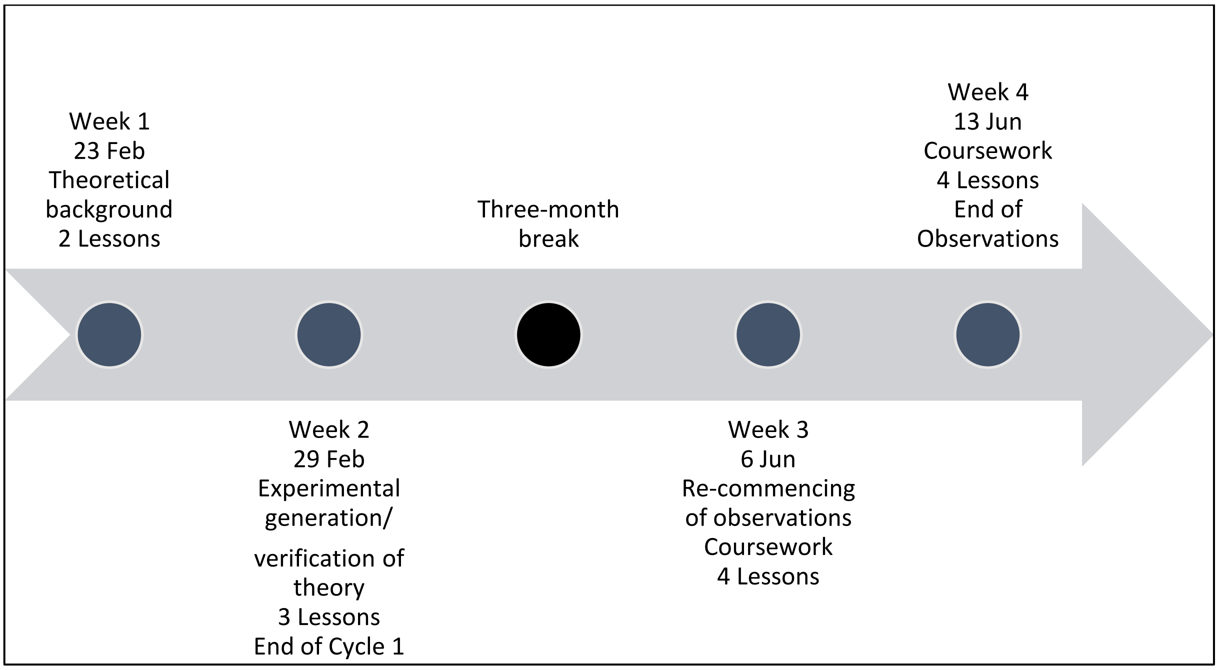


Figure 5: Group 3, Observations timeline

Richards and Farrell (2011) listed checklists, seating charts, field notes, narrative summaries and follow-up conversations as some of the observation tools that may be employed alongside the use of an observation grid with pre-prescribed categories (O’Leary, 2012, p. 51). For the present study, the quantitative observation tool was an observation sheet with a list of twenty codes that represented specific descriptions of interactions (listed in Appendix 1). Video or audio recording of lessons were also undertaken to complement the observation sheet records; for which prior consent was obtained. The design of the observation sheet was based on Flanders Interaction Analysis Categories (FIAC, 1960 in O’Leary, 2013, pp. 50-51). The FIAC was devised for teacher observation and professional development purposes in the USA and consisted of two components: one component was a grid of sixty squares. Each square box represented one minute. The second component was a list of ten coded actions that represented occurrences of either speech or silence. In FIAC the actions were originally listed under three main categories: Teacher Talk, Student Talk and Silence. From the overall of ten actions, five described the teacher’s input, four described the students’ input and one described silence. Of the three overarching categories – Teacher Talk, Student Talk and Silence – the two first had sub-categories labelled Initiation or Response according to the type of talk that was observed. The FIAC was a systematic classroom observation tool for recording classroom occurrences per minute. The observer’s job using the FIAC was to record the actions that happened in each minute of the lesson using the codes numbered 1 through 10. The grid portion of the observation sheet was adapted and used for the purposes of the present study. The codes were considered outdated and incompatible to the activities that had been observed in the pilot observations (Section 4.2.1). There was more than mere “Talk” that occurred in the chemistry classroom. Additionally, the ten codes in Flanders list failed to cover the actions that the researcher aimed to capture as expressions of critical thinking. The new coding that was devised for the study is shown in Figure 6.

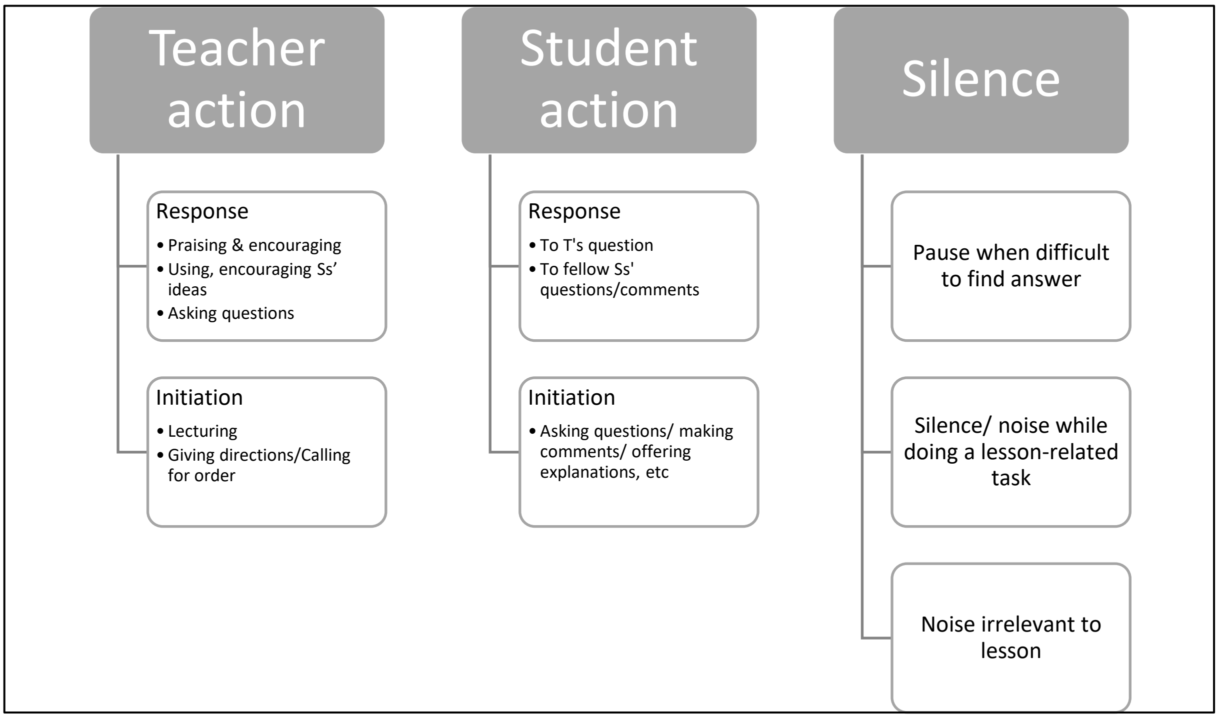


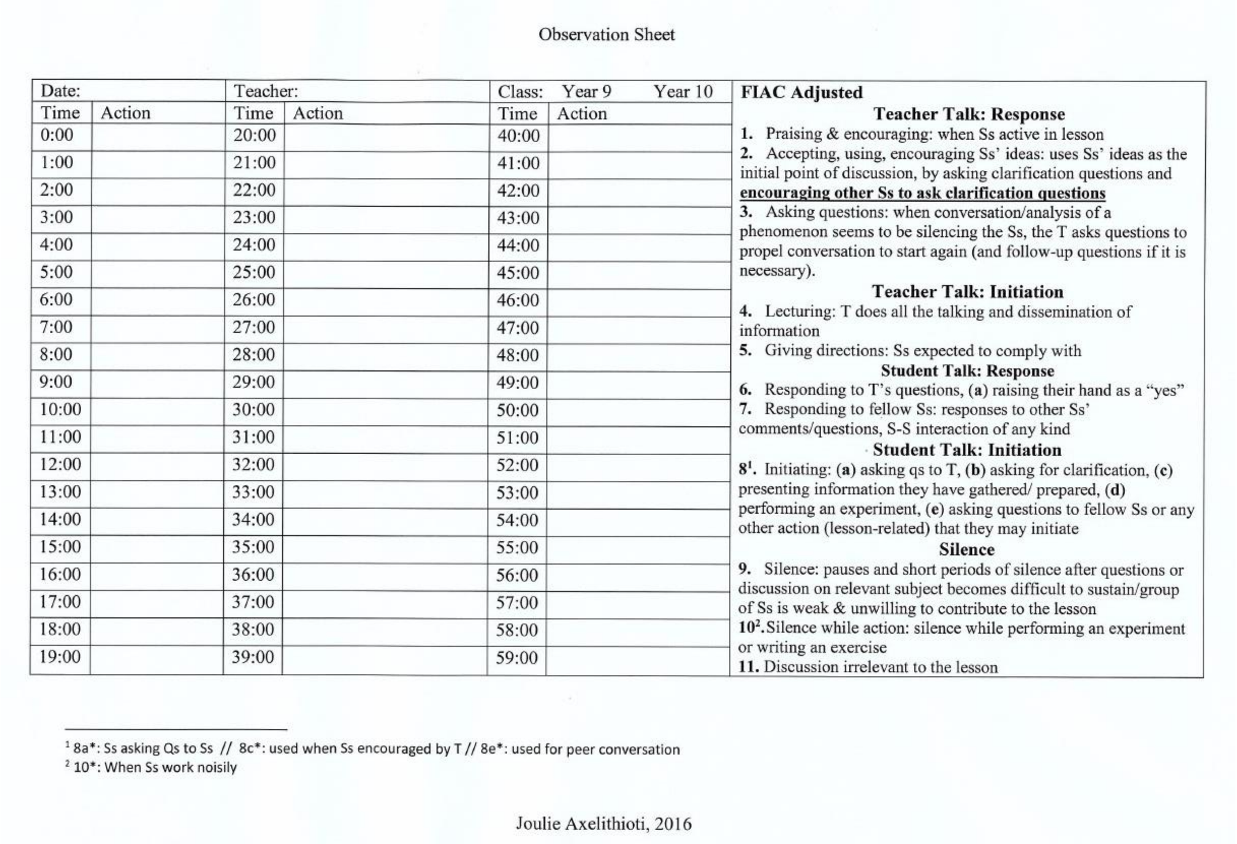
Figure 6: Coding of Actions in the Observation Sheet for the study

The new codes represented a teaching and learning environment that was much more interactive. The square boxes in the grid became short lines, as a small square would not suffice for the description of what happened per minute during the lesson. Observer notes in freestyle writing complemented the lesson observations. The reflective notes served two purposes: on one hand, they highlighted the events that affected the flow of the lesson and changed the atmosphere in the classroom. On the other, they were recorded descriptions of occurrences that left an impression on the observer for qualitative exploration during the analysis. From the codes used in the grid further refinement was required to highlight measurable data in relation to critical thinking. The refinement process follows in section 4.3.3.

4.3.3 Presenting the Codes

The study yielded a large dataset that was broken down to three separate sub-datasets for more effective analysis. The codes from the observation sheets were combined with further observations from the video and audio recordings, interview data and reflective notes from the observer that were recorded pre- or post- observations.

From adapting the original FIAC and adjusted observation grid was produced (Image 3). The adjusted observation sheet had twenty coded interactions as shown in the picture below and can be found in Appendix 1.



Observation Sheet

Date:		Teacher:		Class: Year 9 Year 10	
Time	Action	Time	Action	Time	Action
0:00		20:00		40:00	
1:00		21:00		41:00	
2:00		22:00		42:00	
3:00		23:00		43:00	
4:00		24:00		44:00	
5:00		25:00		45:00	
6:00		26:00		46:00	
7:00		27:00		47:00	
8:00		28:00		48:00	
9:00		29:00		49:00	
10:00		30:00		50:00	
11:00		31:00		51:00	
12:00		32:00		52:00	
13:00		33:00		53:00	
14:00		34:00		54:00	
15:00		35:00		55:00	
16:00		36:00		56:00	
17:00		37:00		57:00	
18:00		38:00		58:00	
19:00		39:00		59:00	

FIAC Adjusted

Teacher Talk: Response

1. Praising & encouraging: when Ss active in lesson

2. Accepting, using, encouraging Ss' ideas: uses Ss' ideas as the initial point of discussion, by asking clarification questions and **encouraging other Ss to ask clarification questions**

3. Asking questions: when conversation/analysis of a phenomenon seems to be silencing the Ss, the T asks questions to propel conversation to start again (and follow-up questions if it is necessary).

Teacher Talk: Initiation

4. Lecturing: T does all the talking and dissemination of information

5. Giving directions: Ss expected to comply with

Student Talk: Response

6. Responding to T's questions, (**a**) raising their hand as a "yes"

7. Responding to fellow Ss: responses to other Ss' comments/questions, S-S interaction of any kind

Student Talk: Initiation

8[1]**.** Initiating: (**a**) asking qs to T, (**b**) asking for clarification, (**c**) presenting information they have gathered/ prepared, (**d**) performing an experiment, (**e**) asking questions to fellow Ss or any other action (lesson-related) that they may initiate

Silence

9. Silence: pauses and short periods of silence after questions or discussion on relevant subject becomes difficult to sustain/group of Ss is weak & unwilling to contribute to the lesson

10[2]**.** Silence while action: silence while performing an experiment or writing an exercise

11. Discussion irrelevant to the lesson

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[1] 8a*: Ss asking Qs to Ss // 8c*: used when Ss encouraged by T // 8e*: used for peer conversation

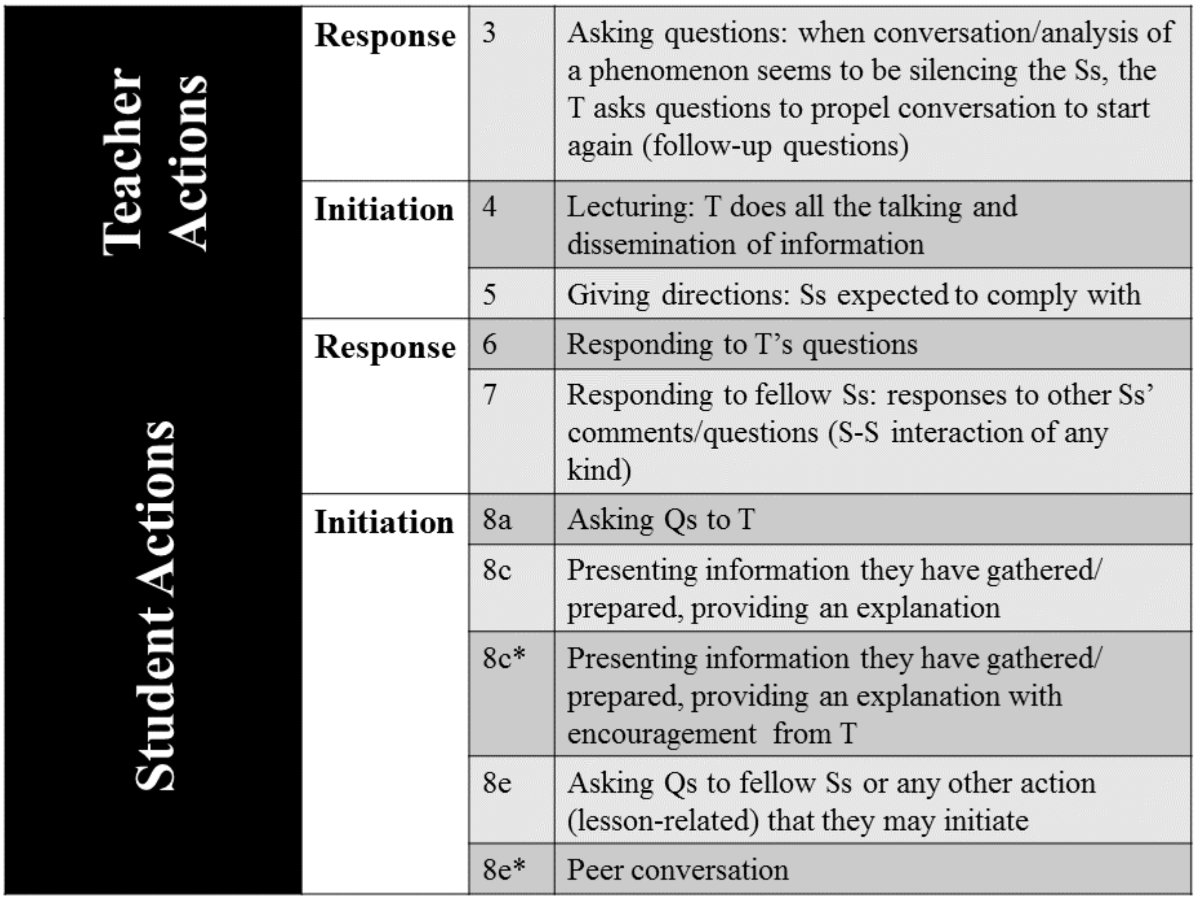
[2] 10*: When Ss work noisily

Joulie Axelithioti, 2016

Image 3: Observation Sheet used for classroom interactions

However, only ten of those codes were considered to contribute significantly and systematically to the investigation of the research questions. The ten codes that were analysed are given in Table 1 below. The codes used were modified from Flanders' (1970) original ten to describe interactions that were most likely to be observed in the chemistry classroom. These interactions were considered to be demonstrations of the students' employment of the CT skills under investigation. Data from the observation sheets and video/audio recordings per Group were treated and analysed in accordance to the selected ten codes. Primary analysis of the video/audio data made it apparent that this set of data best recorded student-student interactions while the observation sheets offered richer, more accurate information on the teacher-student dynamic.

Table 1: Codes analysed in the study

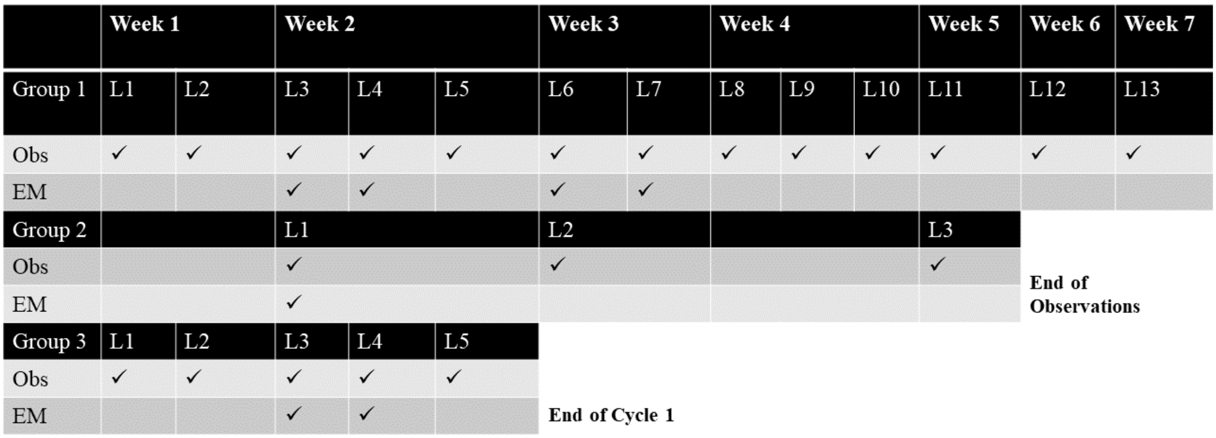


Teacher Actions	**Response**	3	Asking questions: when conversation/analysis of a phenomenon seems to be silencing the Ss, the T asks questions to propel conversation to start again (follow-up questions)
	Initiation	4	Lecturing: T does all the talking and dissemination of information
		5	Giving directions: Ss expected to comply with
Student Actions	**Response**	6	Responding to T's questions
		7	Responding to fellow Ss: responses to other Ss' comments/questions (S-S interaction of any kind)
	Initiation	8a	Asking Qs to T
		8c	Presenting information they have gathered/ prepared, providing an explanation
		8c*	Presenting information they have gathered/ prepared, providing an explanation with encouragement from T
		8e	Asking Qs to fellow Ss or any other action (lesson-related) that they may initiate
		8e*	Peer conversation

4.3.4 External validity comparison

The creation of a new tool for observation necessitated the use of a second observer to check whether the codes were accurate descriptions of the interactions recorded. An external moderator (EM) visited all three groups; a total of seven times (four times to Group 1, once to Group 2 and twice to Group 3). The EM was a psychology graduate with experience in observations from videos. They had prior experience as a research assistant as an undergraduate student. The organisation of the combined visits of the researcher-observer with the EM was preceded by an hourly briefing session of the EM with the researcher. During the briefing session, the researcher explained the purpose and function of the observations as well as the codes on the observation sheet. The briefing took about an hour and following a short introduction to the idea of critical thinking relating to the observation grid, the EM was asked to read the codes and offer examples of interactions the codes described. The researcher provided further feedback and examples to ensure that the EM was comfortable with the use of the grid and codes. The timetabling and organisation of the visits for the EM were organised by the researcher according to EM's availability. The visits of the EM for all Groups took part in the second and third weeks of studies as shown in the table below (Table 2):

Table 2: Timetable of EM visits



	Week 1		**Week 2**			**Week 3**		**Week 4**			**Week 5**	**Week 6**	**Week 7**
Group 1	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13
Obs	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
EM			✓	✓		✓	✓						
Group 2			L1			L2					L3		
Obs			✓			✓					✓	**End of Observations**	
EM			✓										
Group 3	L1	L2	L3	L4	L5								
Obs	✓	✓	✓	✓	✓								
EM			✓	✓		**End of Cycle 1**							

During the lessons, the EM completed the observation sheets using the table of codes and recorded their personal notes, in a similar manner to the observer. A table comparing the data collected by the researcher (Obs) and EM can be found in Appendix 2. Not all codes were compared, only the ten codes found in Table 1 (section 4.3.3) after the data were cleaned to remove codes that represented irrelevant actions – such as noise and chatter – or codes that were merged because of representing very similar actions (as explained in section 4.3.5). The data in this section present counts observed per lesson by the Obs and the EM individually. Graphs that are included depict weighted data from the shared observations. However, where the measurable occurrences were few, actual counts provided more accurate views of agreement or disagreement and for those codes no graphs were produced. Counts were comparable as the lesson durations recorded by Obs and EM show similarities. The exception is Group 3 where the Obs' lesson durations were adjusted to the time the Obs was not participating in the activities of the group. From the graphs, tendencies moving to the same direction between the two observers show agreement, moving to different directions show disagreement. No conclusion can be drawn for Group 2 as there was only one observation in common with Obs and EM. In the case of Group 2 the frequencies are given in the charts to show similarity or discrepancy of observed actions. Frequencies within the same percentile show close agreement. For Group 2 there are several very low frequencies which are attributed to single observations of the described action. These are explicitly explained.

Codes 3, 4, and 5 referred to teacher-centred interactions, which were plentiful. The tables below show the counts of interactions recorded for Groups 1, 2, and 3 (Tables 3, 4, and 5).

Table 3: Obs and EM observation counts for codes 3, 4, and 5 (Teacher-student interaction), Group 1

G1	**3**		**4**		**5**		**Lesson duration**	
	OBS	**EM**	**OBS**	**EM**	**OBS**	**EM**	**OBS**	**EM**
L3	25	7	6	9	13	19	57	59
L4	30	13	13	6	2	20	57	59
L6	58	45	8	15	16	25	57	57
L7	37	15	18	15	5	14	56	57

Table 4: Obs and EM observation counts for codes 3, 4, and 5 (Teacher-student interaction), Group 2

G2	**3**		**4**		**5**		**Lesson duration**	
	OBS	**EM**	**OBS**	**EM**	**OBS**	**EM**	**OBS**	**EM**
L1	39	40	25	22	7	21	45	48

Table 5: Obs and EM observation counts for codes 3, 4, and 5 (Teacher-student interaction), Group 3

G3	**3**		**4**		**5**		**Lesson duration**	
	OBS	**EM**	**OBS**	**EM**	**OBS**	**EM**	**OBS**	**EM**
L3	7	31	1	4	17	25	35	59
L4	17	33	7	16	7	11	47	59

For codes 3, 4, and 5 the measurable data were significantly higher than what was observed in comparison from the student contributions. The charts below - weighted frequencies of codes 3, 4, and 5 – from the EM and the Obs show agreement in tendencies for codes 3 and 5 in Group 1 (Figures 7A and 7C), they are fairly similar for codes 3 and 4 in Group 2 (Figures 8A and 8B), and show agreement in the observations for Group 3 (Figures 9A, 9B, and 9C).

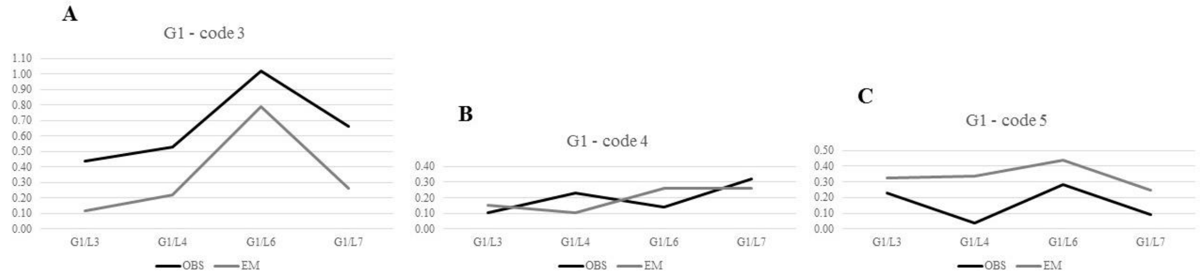


Figure 7: Weighted frequency for code 3, 4, and 5 by Obs and EM, Group 1

Figure 8: Weighted frequency for code 3, 4, and 5 by Obs and EM, Group 2

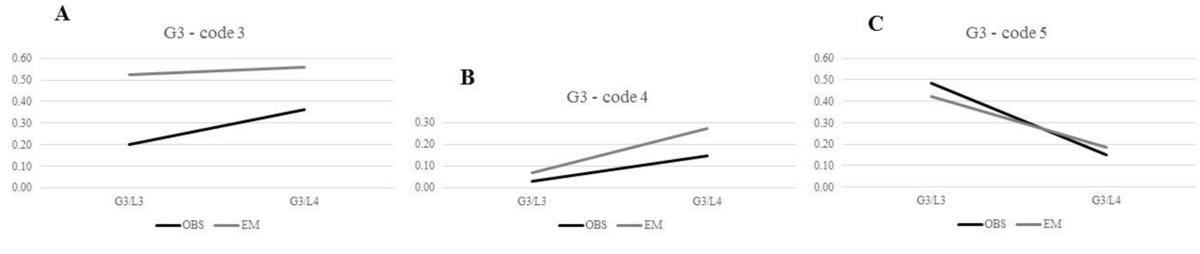
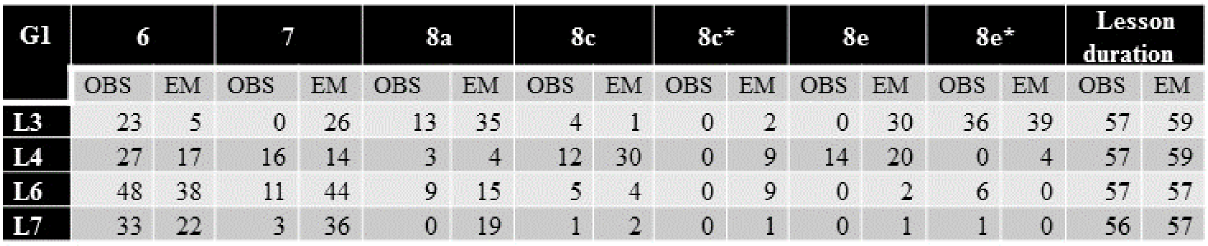


Figure 9: Weighted frequency for code 3, 4, and 5 by Obs and EM, Group 3

Looking at Tables 6, 7, and 8 the counts recorded by the EM are often higher. This was due to the fact that the EM recorded significantly more interactions during the visits with the

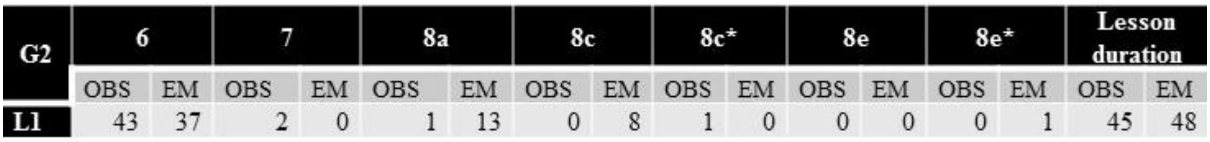
Groups than the Obs. For Group 3, specifically, the lesson durations are also a contributing factor for lower Obs counts as the Obs got involved in the interactions of the group during the experiments, which disrupted the recording of observations. The weighted data reflected that, calculations based on corrected duration of observations for the Obs.

Table 6: Obs and EM observation counts for codes 3, 4, and 5 (student-student interaction), Group 1



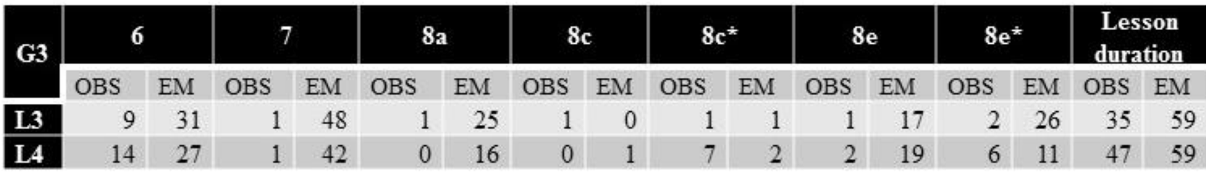
G1	6		7		8a		8c		8c*		8e		8e*		Lesson duration	
	OBS	EM	OBS	EM	OBS	EM	OBS	EM	OBS	EM	OBS	EM	OBS	EM	OBS	EM
L3	23	5	0	26	13	35	4	1	0	2	0	30	36	39	57	59
L4	27	17	16	14	3	4	12	30	0	9	14	20	0	4	57	59
L6	48	38	11	44	9	15	5	4	0	9	0	2	6	0	57	57
L7	33	22	3	36	0	19	1	2	0	1	0	1	1	0	56	57

Table 7: Obs and EM observation counts for codes 3, 4, and 5 (student-student interaction), Group 2



G2	6		7		8a		8c		8c*		8e		8e*		Lesson duration	
	OBS	EM	OBS	EM	OBS	EM	OBS	EM	OBS	EM	OBS	EM	OBS	EM	OBS	EM
L1	43	37	2	0	1	13	0	8	1	0	0	0	0	1	45	48

Table 8: Obs and EM observation counts for codes 3, 4, and 5 (student-student interaction), Group 3



G3	6		7		8a		8c		8c*		8e		8e*		Lesson duration	
	OBS	EM	OBS	EM	OBS	EM	OBS	EM	OBS	EM	OBS	EM	OBS	EM	OBS	EM
L3	9	31	1	48	1	25	1	0	1	1	1	17	2	26	35	59
L4	14	27	1	42	0	16	0	1	7	2	2	19	6	11	47	59

Codes 6 and 7 describe students' response counts to either teacher or peer questions. For Group 1 the Obs saw a definite increase in the number of peer questions that received a (student) reply, whereas the EM observed a momentary increase in Lesson 4 but a decline from that point onwards. The Obs and EM counts also show differences in Group 3, where the EM found codes 6 and 7 to be dropping from the first lesson to the second whereas the Obs found them either stable or ascending. This difference triggered re-investigation based on secondary observations from the video records. When re-counting on secondary observations from the videos, the Obs counts were confirmed or adjusted but still did not agree with the EM counts. Upon reflection, this showed higher sensitivity of the Obs towards student-student interactions and more accurate recording of instances in comparison to the EM. For Group 2 the data show that counts recorded were frequently similar.

Looking at the counts and figures overall, certain interactions were comparatively similarly recorded by both observers while others were not. For instance, the interactions that the Obs and the EM generally agreed on were either teacher asking questions, lecturing, giving instructions, or students replying to and directing questions to the teacher – corresponding to codes, 3, 4, 5, 6, and 8a. The former three interactions, initiated by the teacher, are familiar occurrences in an educational setting both for teachers and students, and so are the latter. Therefore, it was more likely for Obs and EM observations to be in agreement about them as they were distinctly recognisable. The newly devised codes for interactions that emerged under the influence of the CT study presented more of a challenge and agreement was more difficult. Group 2 was used as a baseline due to the different idiosyncrasy of teaching and learning practices and because it was a smaller cohort of students. The teacher of Group 2 led a highly structured lesson with controlled student interactions that were most frequently teacher-led and less so student-led. This had an impact on the counts of codes of student-student interactions.

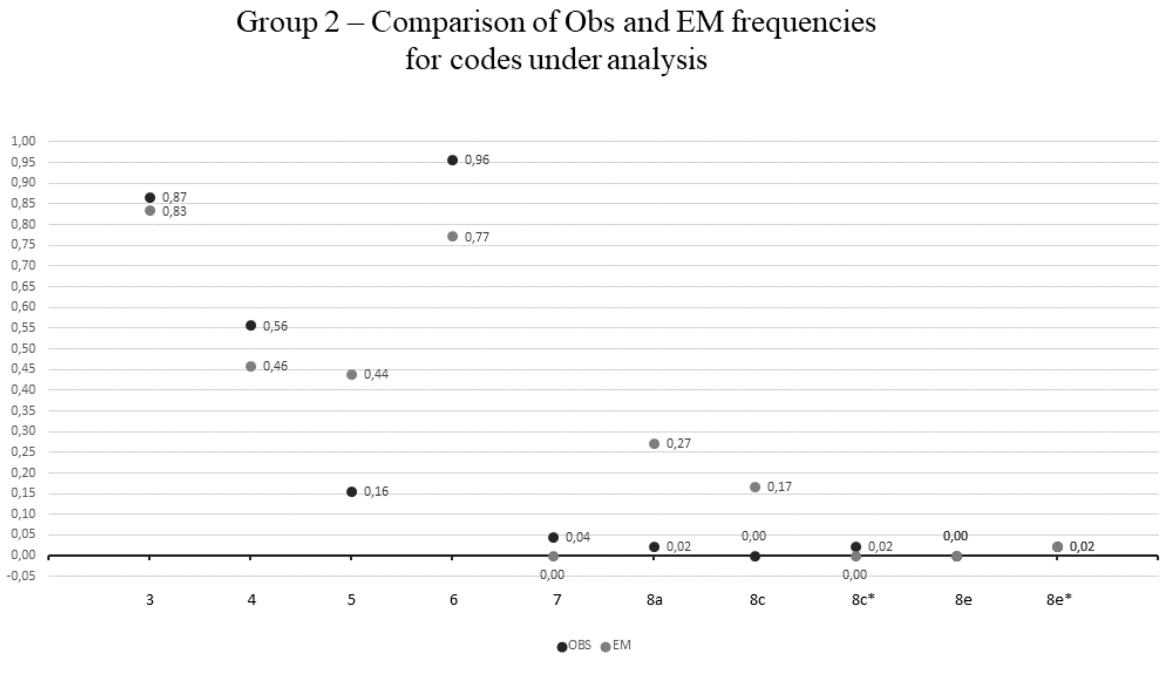


Figure 10: Weighted frequency of all codes for Group2-Lesson 1

Codes for Group 2 were examined in detail (Figure 10). From Figure 10, student interaction codes were relatively poor in count often being zero (Table 7, codes 8c*, 8e, 8e*). Excluding codes 5, 8a, and 8c where EM and Obs clearly disagreed on what they observed, the remaining seven codes demonstrated the tendency to observe actions in similar frequencies –

four out of ten codes followed the pattern of Obs recording higher frequencies to EM (codes 3, 4, 6, and 7), three were either 1 or 0 (codes 8c*, 8e and 8e*) showing similarity rather than difference, and three frequencies were more keenly observed by the EM than the Obs (codes 5, 8a, and 8c). The difference in frequencies of code 5 – teacher giving instructions – could be attributed to lecturing turned to instruction. Code 8a, describing the number of questions the students asked their teacher, the EM recorded 13 such questions, whereas the Obs recorded only 1. However, from the audio data, students showed to be in the habit of replying to questions in an interrogative tone, which could explain the reason occurrences were recorded under different codes. Finally, for code 8c - student production of explanations, arguments or information spontaneously the Obs did not record any whereas the EM recorded eight such instances in the same lesson. The discrepancy for student questions (8a) to the teacher may be due to the bias of the Obs looking for deep questions and missing the questions that were procedural. On the other hand, the discrepancy in code 8c could be due to the EM bias of taking an explanation that was assisted and guided by the teacher to be of more independent nature.

Groups 1 and 3 which had less structured and busier lessons with a lot more interactions happening at the same time, were definitely more challenging in capturing all interactions happening simultaneously.

In addition to the effort to bring in an external moderator, Harry, the teacher of Group 3 expressed interest in understanding the process of recording observations in the classroom and there was discussion with the researcher for Harry to be an internal moderator (IM). As Harry was mentoring a student-teacher, Mary, he felt he could record observations during the lessons along with the Obs. After two attempts, however, he found it challenging to fill in the observation grid, as he wanted to focus his attention to the development of the lessons. The observation records that Harry produced from those attempts had sparse notes with ten or fewer boxes in the grid having been filled. An offer was made to Hannah to moderate internally from the videos her students produced but she found she focused more on herself and self-criticism on her teaching and focused less on student interactions with her and with each other.

4.3.4.1 Acknowledging bias

Despite the fact that we cannot claim absolute agreement between Obs and EM counts and frequencies, there was a considerable number of similar tendencies on the graphs to prove that the devised observation tool used was adequate. Reflection on the points of disagreement highlighted differences of training, opinion and involvement of the Obs and the EM with the study and its premises, which were attributed to respective biases. For instance, certain factors were not taken into consideration when organising and planning the joint observations of Obs and EM. Experience, background and learning/teaching preference of the Obs and the EM were factors that potentially influenced the individual observations. The EM was from a psychology background and their most relevant experience to chemistry learning came from learning it at school. The EM admitted to some bias from personal learning preferences as a student – specifically working better in a firmly structured environment where teacher instructions were frequent and consistent and the roles of the teacher and the students were strictly defined: the former being the dispenser of knowledge and expert and the latter being the recipients of knowledge. The EM expressly pointed out that the type of classroom environment found in Groups 1 and 3 felt confusing. The EM formed an opinion on the study soon after they joined about the impact of an independent project where the students were responsible for gathering their own material and putting together a presentation – even in small groups – with the purpose of informing one another about new theories, presupposed dependence on peers' abilities to explain chemistry. These left the EM uncertain about the quality of the learning. In short, putting themselves in the student position, the EM could not trust that the information organised by the students could in anyway replace the sturdy and secure expertise and teachings generated from the teacher. In that light, the EM showed clear preference and better understanding of a setting similar to that observed in Group 2, and less so in settings similar to Groups 1 and 3.

In terms of observation experience, the Obs had no prior experience observing within research whereas the EM had prior experience as an undergraduate research assistant in a psychology laboratory and with video observations. This made the EM a better-qualified observer. The skill was manifested in the number of observations recorded by the EM per minute which were consistently more than those of the Obs. As the Obs was involved in the design and compilation of the observation grid, the underlying bias was a focus on interactions that would produce a measurable CT result. Accounting for the bias, the Obs' final measurements were based on counts from the secondary observations found in the video and audio data. According to video and audio data, the primary Obs measurements – in-class, in real time – were usually fewer than those from the secondary observations, confirming that the observation grid served better in recording teacher-student interactions and less so student-student interactions.

The Obs had considerably more experience in a classroom as a teacher and in other teaching settings and was familiar with the principles of the study, the code generation process, and had a clear notion of predicted interactions that could have occurred during the lesson. The Obs regulated the visits and was in charge of organising the schedule for both Obs and EM. Scheduling the observations included the initial briefing but no follow-up briefing after the first few observations in order the Obs and EM to debrief one another about the use of codes and the frequency of recorded occurrences. Beyond the EM's initial hourly training there was one follow-up non-scheduled communication – of rather informal nature – with the researcher where the EM suggested the addition of two codes (8a* and 10*) for clarity of recordings. In the first briefing, the EM read the description of each code and offered an example of actions the code might be representing, which were deemed satisfactory. In the follow-up discussion after the second class visit, the EM did not find that the descriptors required altering apart from the suggestion for the additional two codes, which were added. In later feedback after the end of EM's visits, the EM expressed some uncertainty in distinguishing two codes that seemed to describe the same action: codes 8a* and 8e both referred to students asking questions to one another. In the analysis that follows in Chapter 5, the observations under the two codes have been merged under the code 8e.

The different classroom practices may also account for the fluctuations in agreement between EM and Obs. The classroom environment for Group 2 was quiet, controlled, and teacher-centred. There was a clear mark of beginning and end of the lesson. For Groups 1 and 3, the structure was looser and there was no clear mark for the beginning or end of the lessons. As Obs and EM had no agreement about start and end time, each started and ended their recordings autonomously. This created a discrepancy on the produced records regarding synchronisation for commencing and completing the observations apart from "recording from the beginning of the lesson". Therefore, the duration of each observed lesson was often not in agreement (Table 9).

Table 9: Lesson duration in minutes for lessons observed by Obs and EM

	G1/L3	G1/L4	G1/L6	G1/L7	G2/L1	G3/L3	G3/L4
Obs	57	57	57	56	45	35	47
EM	59	59	57	57	48	59	59

Finally, seating arrangements may also have affected agreement between frequencies. In the classrooms of Groups 1 and 3 the Obs often walked around the room to have a more rounded view. When seated, the Obs sat at the right end corner of the classroom with clearer view and auditory capacity of the rows of students on the side. The EM was consistently seated during all visits, positioned at the left end corner of the classrooms. In the classroom of Group 2 the EM and the Obs sat next to each other in the centre at the back of the classroom behind all the students having immediate view of the row of students at the nearest desk, which presented partial obstruction in the observation of the two rows further at the front.

4.3.5 Limitations of codes

From a preliminary overview of the data it became obvious that the codes with multiple letters. i.e. 8a, 8b, 8c, etc. showed some overlap. For instance, code 8a* and code 8e both referred to peer questions. Code 8a* was not in the original observation sheet, rather it was added during the first two observations as an afterthought in collaboration with the EM. As Obs and EM became more familiar with the codes the overlaps became clearly obvious and there was some confusion as to whether each code had been devised for a different purpose. Eventually it was a question of whether one code was more appropriate to use from the other. The Obs used code 8e when capturing student-student questions, and more rarely code 8a*, whereas the EM opted for 8a* to record peer questions. Upon reflection after the EM's visits to the schools, the EM and the Obs agreed that they were recording the say type of interaction each using either 8a* or 8e. As a result, while cleaning the data, code 8a* was converted to 8e and removed entirely.

During the treatment of data it also became clear that several codes that were kept from the original FIAC were not relevant to the study. Codes 1, 2, 6*, 8b, 8d, 9, 10, 10*, and 11 (Appendix 1) did not contribute in any essential way towards describing interactions involving questions, explanations, or arguments. These were not analysed and were consequently removed. On the other hand, code 8c entailed students providing explanations, presenting information or arguments, making observations. These occurrences were not distinct from one another, as they were all considered to contribute towards building an explanation. Code 8b specifically described asking for clarification. This code was removed from the analysis because of the low occurrence as well as the fact that asking for clarification was virtually asking a peer question which was also described by code 8e. The low occurrence of code 8b signified that the clarification questions were recorded via another code (8e) and therefore frequencies for 8b were added to those of 8e. Finally, codes 7 and 8e included the description of "S-S interaction of any kind," however, not many different interactions were recorded under these codes. Code 7 was used for student responses to peer questions and code 8e recorded the occasions that peer questions were captured.

4.3.6 Interviews and Questionnaires

'Teacher interviews' are more accurately described as series of discussions developed between the researcher and the teacher participants concerning the progress of the study and took place following the last lesson observed or at a convenient time for the teachers. The interviews explored the "more complex and subtle" (Denscombe, 2007, p. 175) ideas of critical thinking the teachers were developing but also the observations they made about their students. These unstructured conversations would range from general fact-finding questions: "What activity did you employ today for CT?" to discussions focused on a specific CT skill evident in a lesson, for example, the explanations provided by the students. On such occasions, the questions persisted on how the teacher perceived or observed a behaviour and why the behaviour stood out, with the intention to explore the change in behaviour the teacher noticed and make sure that the teacher's opinion and impression relevant to the study was included and reflected upon.

In addition to recording conversations with the teacher, a short questionnaire of four questions was compiled for Group 3 students at the end of Phase 1 of the study. Dues to time constraints the questionnaire was not completed until the end of Phase 2 for the study (find questionnaire in Appendix 4). The questionnaire was re-organised as part of the second cycle of action research and the data were collected in audio recordings. The questionnaire was finally presented to the students in the form of individual interviews, which were conducted a quiet area in the classroom while the rest of the class were performing their experiments. These student interviews were seen as opportunities for the students to give their personal comments on the study but also allow space for self-expression to show and make use of the CT skills they had been developing. An analysis of the interviews is provided in the next chapter (Chapter 5).

4.4 Introducing the Participants

Two schools gave consent to participate with three in total teaching staff and students two Year 9 cohorts and one Year 10. The schools will be called School 1 and School 2 and the groups Group 1, Group 2, and Group 3 (Sections 4.4.4, 4.4.5, and 4.4.6).

4.4.1 Description of Schools

After an initial contact with the teacher participants, it was clear that there were differences in the ethos and philosophy of learning in each school and would affect their understanding, and the researcher's ability to manage their expectations, of the study.

School 1 was an academy converter and had a mixed population of male and female students, was a state school, and had a higher than average student population with disabilities. The school budget was equally allocated to all departments, so it did not have a science-oriented curriculum. The Ofsted report for School 1 awarded it the description of a good school (point 2) where the leadership took painstaking care to improve the learning experience of the students and addressed issues raised in the time between Ofsted inspections. The GCSE results for the school were good and sustainably improving according to the actions designed by the leadership teams. The school leadership model followed a localised leadership scheme which translated to the Head teachers allocating resources to the Heads of departments and providing the freedom for the resources to be used to the best judgement of the departmental teams.

School 2 was a girls' school. In the Ofsted report it was characterised as a good school and the type of school was comprehensive. In terms of pupil population, School 2 had high ethnic diversity with students not speaking English as their first language. It was a school participating in the pupil premium scheme, which was used to provide additional support and resources to improve student learning.

Both schools had sixth forms with mixed gender population and the progress of the students from the point of entry to the point of exit in GCSEs was that of sustainable improvement.

4.4.1.1 School 1

At the time of the first visit to the school, chemistry was taught following the OCR guidelines and specifications but during the year the specification was undergoing a change to AQA guidelines and specifications (overview of school curricula and syllabi in Table 3 at the end of this sections). School 1 invested in a Continuous Professional Development (CPD) scheme for the development of the teaching staff. The collaboration with the teachers was included as part of the CPD scheme of the school. School 1 participated in the study with a Year 9 cohort and a Year 10 cohort.

Year 9 students had three hours of science per week and the sciences taught were Chemistry, Physics and Biology. School 1 had organised the teaching of the three sciences for Year 9 into teaching cycles. That meant that one cycle was for Physics, one was for Biology and one was for Chemistry and for about 11 weeks at a time, students spent three hours per week doing only one of the sciences. What enabled this type of syllabus organisation was the policy of the science department to allocate one teacher per cohort to carry out the teaching of all three sciences for Year 9. The same teacher would teach chemistry, biology and physics, regardless of their expertise, as the level was considered manageable for any teacher with scientific background.

Year 10 students had five hours of chemistry split in two weeks – 2 hours on Week 1 and 3 hours on Week 2 – all year round. Each science was taught by a specialist, so chemistry was taught by chemists. The syllabus and content of chemistry in Year 10 were a preparation for GCSE exams which was completed in Year 11. The content was more specific and the expectations for learning better defined and refined.

Information relevant to the ethos of the school was gathered from the school website and that was further complemented by requesting and attaining permission to meet with the Head Teacher. From the website, School 1 had several decades of excellent education standards according to their Ofsted reports. The information prospectus of the school presented the guidelines they followed, with emphasis on the diversity of activities, activity-based learning and diversified teaching that took place in the school throughout the year. There were days that were allocated to mixing school population and working on specified skills, such as sports and physical education. School 1 drew confidence from mixing the school experience. That translated to organising field trips, science events, and religious education modules. The prospectus listed different events in the school and it created an impression that activities were constantly taking place in an environment of chaotic order. This fell somewhat in harmony with the CT study from the point of designing an intervention with the ambition to replicate a chemistry lab environment, wherein many things happen simultaneously. A pseudo-authentic chemistry lab environment meant to activate self-reliant thinking, hypothesising and testing/negotiating of the hypothesis among the student participants. It also created a promising expectation for more interactions of the participants – students and teachers – and a different balance in the distribution of responsibility for learning, i.e. students would be allowed to take the lead on more frequent occasions.

One thing that stood out in the website of School 1 was the commitment that was stated towards lifelong learning. School 1 wanted to be constantly innovative and therefore set learning and success goals for the students, naturally, but also for the teachers. This value was shared by the Head Teacher in the interview. The Head Teacher of School 1 described the school as a community facility that was available to the community beyond the capacity of just a school in the traditional sense. The school ran a number of extracurricular activities both during term time and outside of it. Another two values that emerged were the importance and emphasis that the school placed on the involvement of parents in the process and progress of the students' education as well as the encouragement for independent learning, learning that happened in the corners of life of the students that were spent not only in the school premises but beyond. The Head Teacher wanted to inspire students by providing them with leadership models, i.e. the Head Teacher noted that in the science department there was a Head of Science, Deputy Head of Science but simultaneously all teaching staff contributed ideas and exemplary practices in the CPD and department meetings. Other leadership opportunities were also available through school activities inside but also outside of school hours in community-based activities organised on the school grounds. The leadership skills, the independent learning, the building of support mechanisms for student development resonated with the aims of the study for creating an environment in the chemistry class that directed the students to think for themselves, rely on their efforts and observations, and exchange ideas with peers to achieve better understanding of the content.

From the research point of view, it was important for the school to allow the teachers to attempt changes in their practice because that would create a more fruitful collaboration with the researcher. It also meant that the teachers would be actively involved in shaping the project. With the idea of independent learning underlying the efforts of the teachers, it became easier to send students home to build a project of their own about atomic theories, for example, which was part of the content the study focused on (see reference to Group 1 - Lesson 4 in Chapter 5). Since the participants in the study were volunteering their time and effort, working with a school that upheld these values was not planned but it added to smoother, more productive and immediate communication and collaboration with the teachers. It made the presence of the observer automatically accepted by the students and the video recording of the lessons less intrusive and more fun. According to the Head of Science, the students frequently recorded activities in the class, so being filmed was not unusual. The learning philosophy of the school was an overall positive affect in the study.

Table 10: Descriptive summary of Schools 1 and 2

	School 1	**School 2**
End-of-school exam type	OCR but in the process of changing to AQA	OCR but in the process of changing to AQA
Student population	Mixed gender (boys & girls)	Single gender (girls)
Ethos	Independent Learning	Student & teacher excellence
CT Study as	Continued Professional Development	A university project participation
Groups participation	Year 9 & Year 10	Year 9
Number of teachers	2	1

4.4.1.2 School 2

The information for the ethos and philosophy of learning of School 2 came from the school’s website. The Head Teacher’s message in the website cited past times when the school was a training school for the Department for Education. School 2 still participated in school-to-school associations in order to keep being a pioneer in education and had an expressed focus in science and achievement in science. The ethos of the school was to help develop students’ diverse styles of learning in a calm and purposeful environment of mutual respect. The website for School 2 had short and precise statements of purpose and achievement for the in-school activities and was organised with great care. It also stated the roles of staff that were responsible for different activities. This was an indicator of a more managerial type of leadership in School 2 which was later also confirmed by the teacher participant. The teachers belonged to departments that had hierarchical organisation: the teacher talked to the Head of Chemistry who talked to the Head of Science. The messages were carried to higher management – 4 Deputy Administrators, 2 Deputy Head Teachers and finally the Head Teacher – in this hierarchical manner. From the website of the school, it was clear that the provision of education focused on achievement of excellent performance both for students and teachers and there was considerable investment in efforts from the teaching and administrative team into that.

In contrast to School 1, School 2 did not have chemistry, biology and physics cycles. Year 9 groups had 3 hours of science in their weekly schedule which were allocated to one hour per scientific discipline per week with two different teachers. The three subjects were taught simultaneously throughout the year, which meant that there was a constant continuum for each principle all year round. The school also followed OCR guidelines and specifications but was also undergoing a change to AQA (Table 10). This created appropriate circumstances for the interventions for Year 9 cohorts to be developed in parallel. School 2 did not participate in the study for Year 10. In terms of CPD for teacher support, there was no mention of an official scheme. Teacher support was provided within the, or if any particular issues arose these were carried forward by the Heads of Departments.

4.4.2 Description of Participants

There were three teacher participants in the study with three respective cohorts. For the purpose of clarity, the three cohorts of participants are named: **Group 1** – for School 1, Year 9 participants, **Group 2** – for School 2, Year 9 participants, and **Group 3** – for School 1 Year 10 participants. The selection of participants is best described as an opportunity sample, as geographical location was the deciding factor and the process for participant recruitment stopped after the two schools replied positively to participating in the study. Initial email communication led to meetings with the Head of Science, ‘Theresa’, in School 1 and a chemistry teacher who was also the Head of Chemistry at School 2, ‘Samantha’. The decision as to which Year 9 and Year 10 groups of students would participate in the study was made in discussion with Samantha and Theresa respectively. Theresa proposed a collaboration with two of the school's science teachers, 'Harry' and 'Hannah', who were teaching Group 1 and Group 3 respectively. Hannah was a biologist who taught chemistry, whereas Harry was a chemist (Table 11). Additionally, Harry informed the researcher that he would be mentoring a student-teacher, Mary, who would be doing most of the teaching around the time of the study. Samantha, a chemist, was teaching Group 2 herself, so immediately from the first visit she extended an invitation to her lesson with the group for an exploratory observation in order to decide whether the group could participate in the study. Samantha's hesitation about that group stemmed from the fact that the particular cohort consisted of students with low science abilities and a poor record of performance. The group was observed and found appropriate for the study, which finalised the teacher's participation. Samantha originally participated with a Year 10 group that she was teaching, but before that study started, the teacher withdrew her participation.

Table 11: Schools and participants for the study

School 1 **Head of Science, Theresa**	**School 2** **Head of Chemistry, Samantha**
Hannah (biologist) – Year 9, 27 students	Samantha (chemist) – Year 9, 15 students
Harry (chemist) – Year 10, 26 students Mary (student teacher mentored by Harry) – Year 10	

Theresa, the Head of Science in School 1, did not participate with a cohort. However, she was included as a participant in the study due to the fact that she maintained interest and involvement. Theresa offered valuable insight and information explaining the science system in place at School 1 as well as challenges that the teachers often faced in her team and the breakthroughs that they aspired to for their students as a team. Theresa also explained the values that underlay the teaching practices in the school and how they linked to critical thinking, which was the reason she was interested for her team to participate.

4.4.3 Scheduling and Communication

Communication between teacher participants and researcher took different forms according to schedule and convenience. It was initiated via email and conducted in face-to-face meetings. In the meetings the aims of the interventions were explained along with the way of collaborating with the teachers as they were the experts on their classes. As the study was about influencing the attitudes of the students towards more scientifically structured habits of thought, the implementation had to happen in a manner that the teachers would feel comfortable to include in their teaching practice to maximise the output.

4.4.3.1 School 1

For School 1, Theresa incorporated the studies in the school’s Continued Professional Development (CPD) scheme, which automatically created a schedule of meetings as CPD activities were allocated to specific day and time of the school week. Four hourly meetings, one per week, were agreed on, for Hannah and Harry from School 1. The meetings took place during the month of November, about two weeks after the initial meeting at School 1 and determined the lesson schedules and the length of study per group. Consent forms and information sheets (Appendix 6) detailing the use of video or audio recording devices, questionnaires and the presence of and observer in the class were given to the teachers to distribute to their students. These were then returned signed by the parents or students, where deemed appropriate (Year 10). The students and teachers had the chance to opt out of being recorded during the observations, which they assured by returning an extra form specifically designed for opting out of video recordings. The teachers – including Theresa – were also asked to sign the teacher/staff consent forms about being filmed or audio recorded in the class (Appendix 6).

The preliminary interviews with Harry, Hannah and Samantha focused on information dissemination. The researcher explained the core ideas of the study, a definition of critical thinking based on skills that would be the focus of the teaching. The teacher participants described their syllabi and the timelines they would follow and also brainstormed ways that CT opportunities could be introduced to the teaching and learning process. For School 1, the first and fourth meetings were with both Hannah and Harry. The second meeting was with Hannah and included an interview regarding the timeline of the study and the conceptualisation she had of critical thinking after the first meeting (schedule of meeting at Table 12). The third meeting was with Harry and similar topics were discussed (schedule of meeting at Table 12). These meetings provided an initial overview of the teachers’ opinions and awareness of critical thinking, but also served to organise the data collection and completion of the datasets for Groups 1 and 3.

Table 12: Face-to-face meetings, School 1

School 1, CPD meetings November	Participants present	Focus of meeting
Week 1	Hannah & Harry	Explanation of the study, definition of term CT
Week 2	Hannah	Syllabus of Group 1, structure and length of study
Week 3	Harry	Syllabus of Group 3, structure and length of study
Week 4	Harry & Hannah	Concluding preparations and scheduling observations

During the meetings, Harry explained that for the Rate of Reaction he would be mentoring a student teacher, Mary, who would be responsible for the teaching and asked whether that would inhibit the study. It was decided that this would not be a problem, as long as the student teacher agreed to work along with the study. Mary gave consent to work along the lines of the study later in the school year. Initial discussions with Mary focused on an introduction to the study, and Mary was later updated as to the aims of the study and the conditions of the intervention (see section 4.3.5). However, most communications concerning Group 3 remained with Harry, as he was in charge of the cohort and made any decisions with regards to the students' teaching and learning.

4.4.3.2 School 2

After the initial meeting with Samantha, another meeting was scheduled, six weeks later, to finalise the schedule for observations. During that meeting Samantha provided information about the weekly lessons she had with Group 2. She met the group once a week during Period 1. The researcher provided information about how to activate opportunities for critical thinking by creating a pseudo-authentic environment of a chemistry lab in the classroom and allow the students enough time to observe and decide on explanations. This entailed allowing students to converse with one another and take initiative in learning chemistry. Samantha was not able to understand how that would enable her students' learning or critical thinking and pursued the subject with several questions in the meeting but was still happy to take part in the study. In the meeting, observations for Group 2 were scheduled for springtime without specifying the content of the chemistry lessons. As far as content was concerned, the school was undergoing a change of content from the OCR specification to the AQA specification and it was Samantha's job as the Head of Chemistry to adjust the content to be taught. As this had not been completed, it was difficult to finalise the content of the lessons. Further communications via email confirmed that the content was to be the same for School 2 as it was for School 1. However, Samantha was unable to give a specific timeline of when the study would end; as it depended on the progress according to the syllabus and estimated it would not be more than five weeks.

As school 2 did not organise the science subjects in cycles, Group 2 had three hours of science per week, one of which was dedicated to chemistry. In the two meetings with the teacher, descriptions were given about the study and critical thinking and the format that was proposed for the intervention. The format required the teachers to take a step back and let the students take more responsibility of their learning. It meant that the teachers would ideally speak less, so that the students could be encouraged to talk more and provide more explanations about the rationale of their thoughts. Samantha described her teaching practice as one that she would explain to her students what they needed to do and she would then expect them to do it. At the question how she would feel about letting the students take initiatives for their learning within the content of the curriculum, she wondered in what ways that would be possible. She taught a Year 9 and a Year 10 group that could participate, however, she was unsure that the Year 9 group was the type of students the study was suitable for the study as they were of low abilities in science. After an observation for the Year 9 group, it was decided that the group could be participants in the study.

In the second meeting with Samantha, she specified the time for the Atomic Theory teaching to be in the Spring term, and the Year 10 Collision Theory would be taught in late June early July. However, on the day of the last observation with Group 2, with the Year 9 students, Samantha expressed the desire to withdraw from the study concerning the Year 10 cohort, which she did.

4.4.4 Group 1

The observations for Group 1 (School 1- Year 9) lasted seven weeks. A total of thirteen hourly lessons were observed. The lessons covered the greatest part of the chemistry content for the year and were about the atom and atomic theories as has been analysed in Section 4.2.2. The intervention for Group 1 revolved around allowing the students to do more on their own in the class and be able to ask and discuss with their peers the lesson of the day or an in-class activity. The design (section 4.1.1, Figure 1) required that the teacher, Hannah, not directly answer student questions but ask them to reflect on what they knew first and see if they could come up with the answers themselves. As the observations continued along with the syllabus, the students would be expected to progressively work more autonomously on projects, search and bring information to class beyond that found in their textbook, and present in front of the class. The teacher would ensure that opportunities would be provided for observations; for instance, during experiment demonstrations or completing experiments with the use of additional follow-up questions to activate inferential conclusions for elements of the Periodic Table.

Given the study's principle for close collaboration with the teacher participants, and in accordance to the collaborative action research method, the lesson plans were tentative and subject to change. Activities were introduced or re-used, based on how well they seemed to work from lesson to lesson. As the lessons followed one another closely in time within the week and from week to week, changes were also made in activities based on the teacher's assessment; even if she was unsure of the effectiveness of any change. The intervention was considered successfully implemented, from the teaching point of view, when enough opportunities were provided for students to exercise and demonstrate the CT skills analysed in Chapter 3 (further analysis is provided in Chapter 5). Hence, it was an advantage that chemistry lessons were organised as a cycle because students could focus on just one subject at a time and receive consistent input so that they became more familiar with it. On the other hand, having the two cycles of chemistry removed by ten to twelve months – from the previous year to the next – also presented a challenge in terms of recalling knowledge learned before and connecting it to current content.

4.4.5 Group 2

Observations with Samantha were delayed due to her heavy work schedule re-designing the chemistry content and delays in communication. The intervention for Group 2, Samantha's Year 9 class followed the same design as the one for Group 1. However, upon commencing the observations, the teacher informed the observer, that the observations would only last four weeks until the Easter school break, because this was how long the atom and atomic theory content was designed to last. Based on the short time that was given, the study had to be rethought. Samantha opted for audio recording of the lessons and the observer, typically sat at the back of the classroom at a table and kept notes of the lesson. For this set of observations 3 hourly lessons were recorded. There was reflective discussion with the teacher before and after two of the three lessons but she was not comfortable implementing any of the suggestions that were made in terms of the study design and philosophy. Samantha’s opinion about critical thinking was that it sounded more like a luxury, which the intensive exam regime that was followed in the school could not afford. She thought about critical thinking when thinking of science in general, but she could not see how it would work in the class without requiring a considerable time investment. Therefore, Samantha and her class were treated as a control group, a baseline for what happened in a class without any intervention. As mentioned, one class does not provide generalizable data. The value of this dataset is the presentation of another type of classroom reality, which complements the bigger picture of benefits and challenges faced in educational research. Also, Samantha’s views on critical thinking in relation to chemistry education and the way they are expressed throughout the teacher-researcher meetings are of great interest.

4.4.6 Intervention – Significance of experiments: Year 9

The Year 9 syllabus did not include many opportunities for hands-on, experimental experiences. For that reason, the experiments that the syllabus included were reviewed for the specific significance they had for the study. Two different experiments were scheduled to be conducted with the two Year 9 cohorts, which in the study they served the same purpose: to accentuate observation and motivate explanation. For one cohort (Group 1), the first experiment was scheduled on the very first chemistry lesson to show how fire changes the state of matter which was designed to help students start thinking in the microscopic scale. This experiment was originally demonstrated and then done by the students, while safety and precaution regulations were applied. The second experiment was done as a demonstration where the teacher used elements of the first group of the periodic table – Lithium, Sodium, and Potassium – to show how reactions became more violent when the element was added in water. Despite the fact that students would not perform this experiment themselves, the goal was to make sure that the students observed closely, described and drew conclusions from the obvious changes in element reactions.

The experiments for the second Year 9 cohort (Group 2) were done in the same lesson, one as a demonstration from the teacher who showed how the lack of oxygen affected a burning flame. For the other experiment, the teacher first demonstrated it and then the students did it in small groups. This also related to burning a metal to show how the metal burned in the presence of oxygen from the air. Scheduling few experiments with the Year 9 participants provided the opportunity and time for reflection in the lessons and a more philosophical approach in terms of allowing conversation to develop and lessons to be based on narratives about the connection of chemistry to other sciences, life, nature, societies. These opportunities meant to create space for verbalising ideas and thoughts as well as linking to new content via a critical thinking process.

4.4.7 Group 3

The intervention for Group 3, the Year 10 group, had to be designed on a different basis from the Year 9 groups because of the different – richer – content, the more advanced thinking skills expected from older students and their competence and confidence in performing experiments. As previously noted, the school collaborated with universities around Birmingham to mentor student-teachers, so Harry, the group teacher, was joined by Mary, a student teacher, during the period of two weeks of the first cycle of intervention. The design for observations of Group 3 was around experimental content for the introduction of collision theory and the exploration of the factors that affect the rate of reaction and the successful collisions in the liquid state. The content was very specific and it was covered in the period of two weeks, in five, hour-long lessons. This worked well with the Year 10 cohort because the experiments and the intervention were more structured and the circumstances of the experiments were designed to target the specific CT skills under investigation. Students would receive two theoretical lessons that connected the formation of new products in reactions to the notions that the environment of the experiment affects the rate of a reaction that would be followed by three experimental lessons.

In line with the philosophy of boosting independence and motivation of thought in the class, Harry and Mary were asked to deflect or bounce back questions from the students, even in the theoretical lessons, encourage retrieval of prior knowledge and aim at students making observations independently and contributing to a peer debate about how experiments were observed. This practice should initiate explanations to account for observations and conclusions students drew from these observations, which would lead to forming a theory and debating formulated theories with peers. To that end, each of the three lessons-experiments was designed to provide different results for each team doing the experiment. Reactants had different titles of concentration, water baths were at different temperatures, size and surface area of solid phase varied for the respective experiments. Each experimental lesson had a different design: (a) the first used only titrations, (b) the second lesson was an observation of an experiment about surface area followed by discussion of observations, and (c) the third lesson included two different experiments, each experiment having two stations and each team visiting only one of the two stations per experiment. In the first experiment, the aim was to propel collaboration by asking students to compile enough data per team to collectively create the titration curve relating concentration to rate of reaction. Each team represented a point on the curve. In the second experiment the demonstration of the same experiment was organised at two ends of the table one conducted by a student group, on the other by the teacher. Discrepancies in the procedures for conducting the experiment were implemented in order to test observation skills and link those discrepancies to conclusions. Students were to draw conclusions from the difference in results. The third lesson tested the use of catalyst and the influence of different temperatures. Four stations were set up, two with two different catalysts and another two with water baths at different temperatures. Each team was to visit one station for temperature and one for the catalysts and compare their results with other teams in an effort to verify results and discuss potential explanations when results did not agree.

At the end of the two weeks, it was obvious that the short-term study with Year 10 had not manage to cover the expectations of the study, had however, revealed potential in the event of a longer lasting Phase 1. This caused the rethinking of the study. On one hand, the reasoning behind organising experiments with different outcomes per team founded on the premise that the difference in results would activate the students’ curiosity and would in turn prompt discussion, observation not only of own actions but of actions others, questions and debates and in time explanations of rationale, argumentation, and the formation of theory, hypothesis or opinion. On the other, the rate of reaction was a unit investigated twice within the school year, once before the end-of-year exams and once again at the end of the school year as coursework. This extended the investigation from a single chance to observe the progression of students’ CT skills grow to evolving the study in two cycles. In the first cycle the instrumental encouragement from the teachers towards CT was the starting point to help students progressively express CT skills spontaneously. The content of the rate of reaction was investigated twice within the school year, once before the end-of-year exams and once again at the end of the school year as coursework which would be utilised to observe students' CT skills in the absence of any intervention.

In the Summer term during coursework, while the students conducted the same or similar experiments testing the rate of reaction, they would be informally observed. Coursework was described as a chain of lessons that spread over two to three weeks that focused on a single set of activities. The students received intensive science lessons that amounted to seven or eight hours per week. For the Year 10 group the focus of coursework was revisiting Collision Theory, further exploring the Theory and conducting a similar series of experiments where most variables remained stable and only one factor was examined each time. That way the students became quickly familiar with the experimental procedure and had the chance to focus on the observation of the variable that was changing, i.e. volume of gas emitted while time remains stable and concentration of acid varies but is pre-set. The second round of observations with Group 3 was three months apart from the first one and in revisiting the group gave the ability to observe if there were any long-lasting effects of the study from the Spring to the Summer term.

The second round of observations were neither video-recorded nor coded on observation sheets as it was considered more important to interact with the students to find out what they remembered and how it affected their performance in the experiments. All the interactions in the second cycle were recorded using reflective notes and audio-recordings of all conversations. Simple questions were asked during the observations to ascertain the students' knowledge of the Theory and whether their skills for inference, explanation, and sharing information had been influenced by the critical thinking study undertaken in the Spring term. Additionally, a four-question reflective questionnaire for student responses was added in this design, which was completed orally because of time constraints. The questionnaire – turned short interview – was added for the chance of self-expression about chemistry and its influence on the way of perceiving information and framing students' thinking. In the analysis following in Chapter 5, the inclusion of the questionnaire added a valuable testimony for students' expression of critical thinking.

4.5 Moving Forward: Data Collection and Analysis

Overall, twenty observation sheets were completed by the observer and eight by the external moderator (EM, see section 4.3.3). There were also twenty-five audio-recordings made of discussions with the teacher participants and two reflection comments on teacher-researcher discussions were collected. Six lessons were audio-recorded and two audio-recordings were made of students' replies to questions from the questionnaire. There were also 424 video records made by the student participants, 98 photographs taken of classroom interactions.

4.5.1 Ethical considerations

A study involving students under the age of 18 required consideration of ethics and approval from an ethics committee to ensure that the study, the methods for data collections, the type and storage of the data were all according to the rules and regulations of the Data Protection Act 1998, covered in detail in the Code of Practice of the University of Birmingham. According to this, the well-being of all participants ought to be upheld within the research and to that end, we discussed the implications of a critical thinking project in Year 9 and Year 10 chemistry classrooms both with the research leads as well as with the teacher participants. The ethical considerations were about students being video- or audio-recorded while in chemistry lessons following their assigned school schedule. As a result, four documents were produced, two forms of consent, one for student participants and another for teacher participants and two letters of information for students/parents/guardians and staff respectively. The student consent forms required a parent or guardian signature. They explained the study and the methods of data collection, they informed that an observer external to the school would be sitting in the lessons taking notes regarding the lessons. The consent form provided additional information for the usage and storage of the material collected and offered participants the opportunity to opt out of being filmed or even withdraw consent for their data being used, which they could do until the end of the school year. The opting-out date was a safety measure to give students several months after the end of the data collection to withdraw before the analysis commenced.

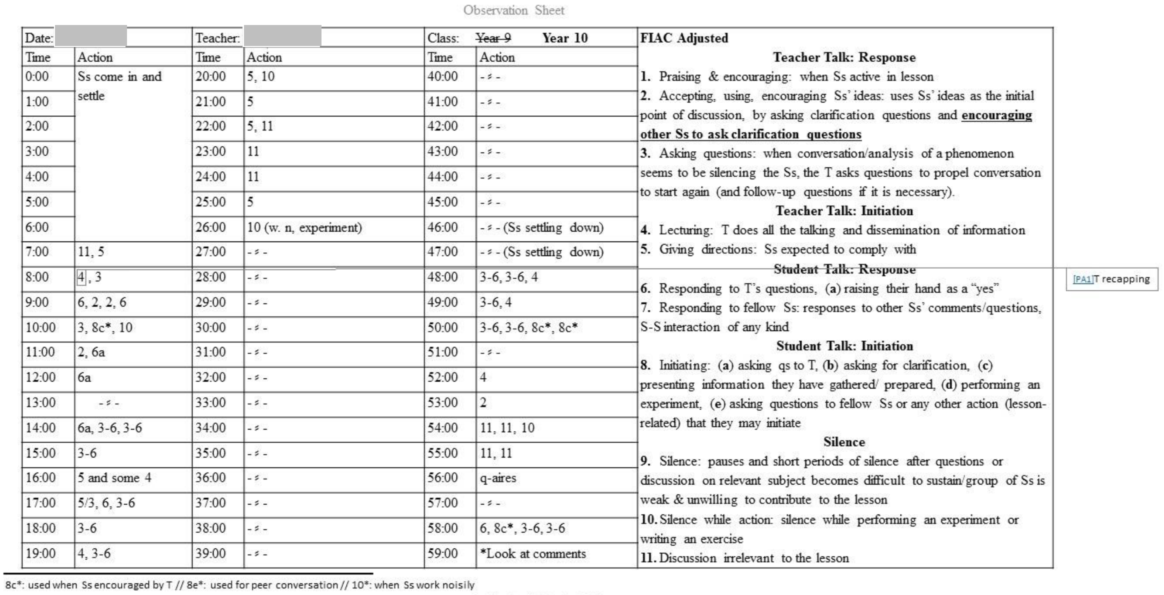
For Group 3 there was a designed Phase 2 of data collection which again was dated about a month before the end of the school year and within that time students still had the chance to withdraw from the study. The student consent form had an attached form that asked students to sign it in the event they wanted to opt out of being filmed. In collaboration with the teachers the team decision was that for students who opted out of being filmed two options were available: to either be moved to another group or to be the ones holding the camera so that their images would not be captured. Two students opted out of being filmed out of the 68 and after discussing their options with their teachers they decided to be the ones holding the cameras and not move classes. Additionally, the teacher of Group 2 expressed concern and reluctance about her classes being filmed and instead offered the alternative of having the lessons audio-recorded. This did not have an impact on the data collection for Group 2 because there were few visits planned with that group, and the group was very quiet throughout the lesson answering questions only when asked. The lessons were accordingly audio-recorded and transcribed during the data analysis. Group 2 participants were offered the same opting-out flexibility till the end of the school year. The letters of information re-iterated the study, consent, and withdrawal information and included contact details with the researcher in the event that participants had queries or wanted to opt out. No participant withdrew their participation.

The University of Birmingham Ethics Committee gave approval for the study and data collection as well as the consent forms and information letters and the teachers also agreed to allow access to their classes and students. Having addressed the concerns of ethics in research successfully both for the ethics board and the participants, signed consent forms were gathered and the study went ahead.

4.5.2 Recording the observations

The observation sheet used for the study can be found in Appendix 1 to the design discussed in section 4.3.2. The codes used corresponded specifically to activities found in chemistry (science) lessons; as they also made provision for the recording of experiments, collaborations and independent study time or activities while the cohort was still in the class, which might not be typical occurrences in non-science subjects.

An observation sheet was used for each of the observer’s visits to a class. According to the schedule of each group, the observer entered the class before the beginning of the lesson, sat at the back of the classroom and used an observation sheet, pen and timer to track the change of time and move to the next minute line. In the only occasion where two lessons overlapped, the observer spent the first half of the lesson in one class and the second half in the other. The observation sheets for both lessons were completed later, based on the video recordings of the two lessons. An exemplar of a completed observation sheet is shown in Figures 11 and 12. The use of observation sheets provided a means for measuring the occurrences of each type of interaction and they were analysed in conjunction with the reflective notes (see section 5.1).



Observation Sheet

Date: [redacted]		Teacher: [redacted]		Class: ~~Year 9~~ **Year 10**	
Time	Action	Time	Action	Time	Action
0:00	Ss come in and settle	20:00	5, 10	40:00	- 〃 -
1:00		21:00	5	41:00	- 〃 -
2:00		22:00	5, 11	42:00	- 〃 -
3:00		23:00	11	43:00	- 〃 -
4:00		24:00	11	44:00	- 〃 -
5:00		25:00	5	45:00	- 〃 -
6:00		26:00	10 (w. n, experiment)	46:00	- 〃 - (Ss settling down)
7:00	11, 5	27:00	- 〃 -	47:00	- 〃 - (Ss settling down)
8:00	4, 3	28:00	- 〃 -	48:00	3-6, 3-6, 4
9:00	6, 2, 2, 6	29:00	- 〃 -	49:00	3-6, 4
10:00	3, 8c*, 10	30:00	- 〃 -	50:00	3-6, 3-6, 8c*, 8c*
11:00	2, 6a	31:00	- 〃 -	51:00	- 〃 -
12:00	6a	32:00	- 〃 -	52:00	4
13:00	- 〃 -	33:00	- 〃 -	53:00	2
14:00	6a, 3-6, 3-6	34:00	- 〃 -	54:00	11, 11, 10
15:00	3-6	35:00	- 〃 -	55:00	11, 11
16:00	5 and some 4	36:00	- 〃 -	56:00	q-aires
17:00	5/3, 6, 3-6	37:00	- 〃 -	57:00	- 〃 -
18:00	3-6	38:00	- 〃 -	58:00	6, 8c*, 3-6, 3-6
19:00	4, 3-6	39:00	- 〃 -	59:00	*Look at comments

FIAC Adjusted

Teacher Talk: Response

1. Praising & encouraging: when Ss active in lesson

2. Accepting, using, encouraging Ss' ideas: uses Ss' ideas as the initial point of discussion, by asking clarification questions and **encouraging other Ss to ask clarification questions**

3. Asking questions: when conversation/analysis of a phenomenon seems to be silencing the Ss, the T asks questions to propel conversation to start again (and follow-up questions if it is necessary).

Teacher Talk: Initiation

4. Lecturing: T does all the talking and dissemination of information

5. Giving directions: Ss expected to comply with

Student Talk: Response

6. Responding to T's questions, (**a**) raising their hand as a "yes"

7. Responding to fellow Ss: responses to other Ss' comments/questions, S-S interaction of any kind

Student Talk: Initiation

8. Initiating: (**a**) asking qs to T, (**b**) asking for clarification, (**c**) presenting information they have gathered/ prepared, (**d**) performing an experiment, (**e**) asking questions to fellow Ss or any other action (lesson-related) that they may initiate

Silence

9. Silence: pauses and short periods of silence after questions or discussion on relevant subject becomes difficult to sustain/group of Ss is weak & unwilling to contribute to the lesson

10. Silence while action: silence while performing an experiment or writing an exercise

11. Discussion irrelevant to the lesson

[PA1]T recapping

8c*: used when Ss encouraged by T // 8e*: used for peer conversation // 10*: when Ss work noisily

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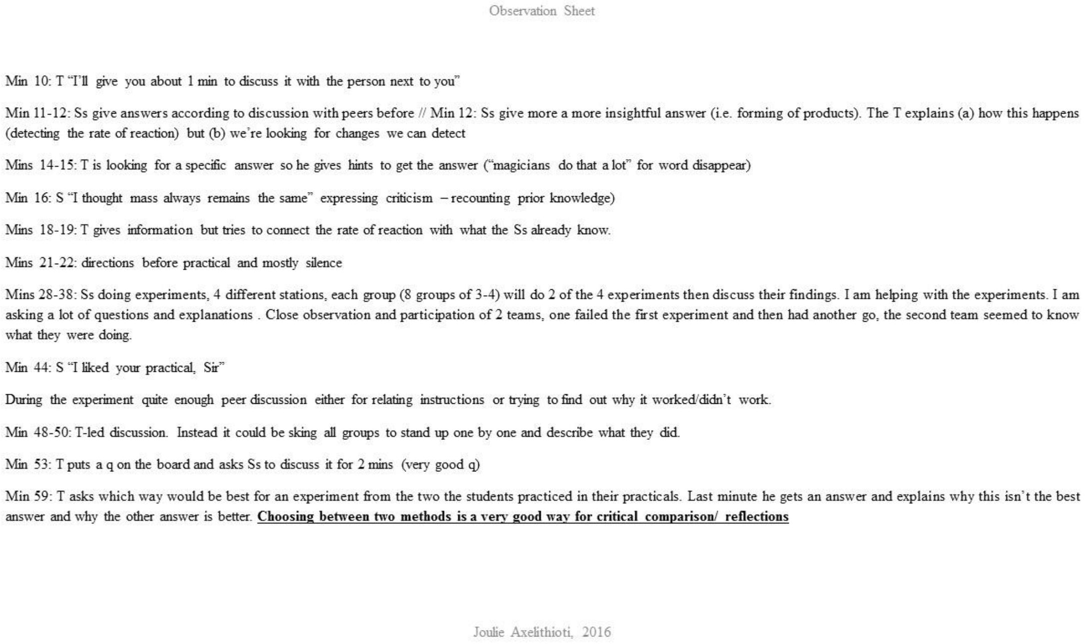
Figure 11: Observation Sheet, page 1



Observation Sheet

Min 10: T "I'll give you about 1 min to discuss it with the person next to you"

Min 11-12: Ss give answers according to discussion with peers before // Min 12: Ss give more a more insightful answer (i.e. forming of products). The T explains (a) how this happens (detecting the rate of reaction) but (b) we're looking for changes we can detect

Mins 14-15: T is looking for a specific answer so he gives hints to get the answer ("magicians do that a lot" for word disappear)

Min 16: S "I thought mass always remains the same" expressing criticism – recounting prior knowledge)

Mins 18-19: T gives information but tries to connect the rate of reaction with what the Ss already know.

Mins 21-22: directions before practical and mostly silence

Mins 28-38: Ss doing experiments, 4 different stations, each group (8 groups of 3-4) will do 2 of the 4 experiments then discuss their findings. I am helping with the experiments. I am asking a lot of questions and explanations . Close observation and participation of 2 teams, one failed the first experiment and then had another go, the second team seemed to know what they were doing.

Min 44: S "I liked your practical, Sir"

During the experiment quite enough peer discussion either for relating instructions or trying to find out why it worked/didn't work.

Min 48-50: T-led discussion. Instead it could be sking all groups to stand up one by one and describe what they did.

Min 53: T puts a q on the board and asks Ss to discuss it for 2 mins (very good q)

Min 59: T asks which way would be best for an experiment from the two the students practiced in their practicals. Last minute he gets an answer and explains why this isn't the best answer and why the other answer is better. **Choosing between two methods is a very good way for critical comparison/ reflections**

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Figure 12: Observation Sheet, Page 2

4.5.3 Interviews with Teachers

As explained in 4.3.5, there were two types of interviews undertaken with the teacher participants: preliminary interviews in the form of semi-formal discussions prior to the class visits, and interviews as a reflection-on-action mechanism following class visits (Schön, 1983). Table 13 shows the number of interviews with each of the teacher participants classified as prior to or during the class visits.

Table 13: Teacher participants' interview data

Teacher Participant	Number of Interviews	Preliminary to class visits	During class visits
Hannah (Group 1 - School 1)	13	5	8 (plus a reflection commentary)
Samantha (Group 2 – School 2)	3	1	2
Harry & Mary (Group 3 – School 1)	6	4	2 (plus a reflection commentary)
Theresa Head of Science, School 1	2	0	2
Head Teacher, School 1	1	0	1
Total	25	10	15 (plus 2 reflection commentaries)

4.5.4 Video & Audio Recordings of Lessons

To ensure that the majority of actions and interactions within the energetic groups of student and teacher participants were captured, video and audio recordings of lessons were necessary. This was because the pilot observations identified instances where careful analysis of students' actions elicited examples of critical thinking behaviour.

School 1 provided i-pads per observed lesson for both Group 1 and Group 3, and all recordings were made using school devices, thus providing digital video recordings of the observed lessons.

For Group 1, there were three or four recording devices in the classroom on all occasions. At the teacher's suggestion, the students undertook the task of video recording the lessons. This mainly resulted in the cameras directed towards the front of the class, which were diverted to capture student-student interactions with teacher reminders. This produced videos of teacher actions and teacher-student interactions, student presentations of fact files and students standing up and writing on the board. As the observations progressed the students were keener to record the interactions happening at their desks. This was because the teacher gave in-class activities that the students completed in teams with increasing frequency. The different locations of the devices recorded different groups of students; including the actions of students sitting further up front from the position of the camera. The types of interaction also varied during those occasions where students worked in groups. In this group the videos recorded student actions and interactions, worksheet progress and in-class activities (Chapter 5).

For Group 2, the observer collected two audio recordings of the second and third lessons. Samantha did not implement any suggestions in her teaching practices; hence the participation of Group 2 was that of control group. There was no audio recording of the first lesson observed for technical reasons.

The Year 10 study (Group 3) focused on experiments and was completed in two separate periods. For the first phase, which lasted two weeks, video recordings were collected the second week for three lessons, all of which were based on experiment performance. Group 3 was divided into nine working teams and each team had their own recording device for all three lessons. At the suggestion of the teacher, Harry, the students did the recording of the lessons. The design of the experiments meant that neighbouring groups performed similar but not the same experiments. Each group was made up of three to four students that worked together. Two performed the experiment and one recorded the efforts. The recordings were not continuous, resulting in approximately 120 video clips of between 1 and 40 minutes in duration. The videos captured the efforts of the students to conduct the experiments successfully. As discussed in sections 4.3.1, 4.3.2, and 4.4.7, the second half of the study with Group 3 was completed in another two weeks of class visits in June. These visits were not recorded on video as the study was re-adjusted to use different methods of data collection.

4.5.5 Student Questionnaire

The student questionnaire was completed in the form interviews and took place with students from Group 3 only during the second phase of class visits. The questionnaire was originally designed to be delivered at the end of the first phase. Time limitations did not allow for that to happen at the planned lesson and the interviews with students were re-scheduled at the end of Week 4, which was in Phase 2. Students were asked the same four questions whose purpose was to gauge attitudes towards chemistry, find out whether the cohort had an overall opinion about the lessons and how they viewed their performance in chemistry. Twenty interviews were gathered in total. In the analysis that follows in the next chapter, critical comments made by the students are highlighted.

4.5.6 Ethnography as a Method for Data Analysis

An ethnographic approach was used for the analysis of the data, which was informed from Bryman's (2012, p. 432) description of ethnography towards the analysis of research outcomes. Ethnography was chosen as a method that would allow the seamless interweaving of data collected with the use of different methods, all of which aimed to illustrate a path of change in CT classroom practice – not merely teaching but also learning. After collecting the data, the challenge was to collate the different data elements for three different groups and their teachers with different interventions and timelines. The analysis included descriptive timelines of events that had a significant impact on the classroom practice for students and teachers. The observed classroom interactions were categorised in Student – Teacher interactions that could influence critical thinking (ST) and Student – Student interactions that inferentially involved critical thinking (SS). The *Interactions* of interest for this study were defined as actions that involve two or more participants who have a verbal exchange. Verbal exchange was the way questions, explanations and arguments could be expressed, which made up the measurements for CT. There were other materials that were used during those interactions but unless there was speech, or talk, they were not analysed. Iconic descriptions, i.e. the instructions of an exercise captured on video may be referred to, serving a specific purpose, which was made immediately obvious. A list of the descriptions of the codes used for the two themes, ST and SS, are presented in Table 14 below. Table 14 is the full set of codes that were used during the data collection. In the data analysis, however, only ten codes were analysed (Table 1, Section 4.3.3).

In the analysis, the data from the records of observation were aggregated per group per code in order to depict the general tendencies in the lessons, i.e. time spent doing an experiment, count of Q and A; count of types of skills students employed to perform a successful experiment. This type of organisation of the quantifiable data had the purpose of identifying whether the lessons were delivered in a lecture-like practice, or the classroom practice required the students' constant participation and input. This aspect closely linked to the research questions looking to determine how different teaching practices contributed – or not – to the students' development of criticality.

The data for the study were gathered using four different methods: the observation sheets, the video and audio recordings of lessons, the teacher interviews, and the research reflection notes. Table 15, below, shows the sets of data collected per group of participants.

Table 14: Codes used to describe student (S) and teacher (T) interactions in the classroom

Teacher Actions	**Response**	1	Praising & encouraging: when Ss active in lesson
		2	Accepting, using, encouraging Ss' ideas: uses Ss' ideas as the initial point of discussion, by asking clarification questions and encouraging other Ss to ask clarification questions
		3	Asking questions: when conversation/analysis of a phenomenon seems to be silencing the Ss, the T asks questions to propel conversation to start again (follow-up questions)
	Initiation	4	Lecturing: T does all the talking and dissemination of information
		5	Giving directions: Ss expected to comply with
Student Actions	**Response**	6	Responding to T's questions
		6a	Responding to T's questions raising their hand as a "yes"
		7	Responding to fellow Ss: responses to other Ss' comments/questions (S-S interaction of any kind)
	Initiation	8a	Asking Qs to T
		8a*	Asking Qs to Ss
		8b	Asking for clarification
		8c	Presenting information they have gathered/ prepared, providing an explanation
		8c*	Presenting information they have gathered/ prepared, providing an explanation with encouragement from T
		8d	Performing an experiment
		8e	Asking Qs to fellow Ss or any other action (lesson-related) that they may initiate
		8e*	Peer conversation
Silence		9	Silence: pauses and short periods of silence after questions or discussion on relevant subject becomes difficult to sustain/group of Ss is weak & unwilling to contribute to the lesson
		10	Silence while action: silence while performing an experiment or writing an exercise
		10*	Noise while action: noise while performing an experiment or writing an exercise
		11	Discussion irrelevant to the lesson

4.5.6.1 – Prior to data presentation and analysis

Once all data were collected, there was an original overview of the datasets based on the different methods of collections to affirm a strategy for analysis. Because the entire design of the data collection was based on observations of coded interactions with a grid and video/audio recordings, the analysis was thematised from the stage of conceptualisation and therefore the analysis was by design thematic, with pre-decided themes that related to questions, explanations and arguments. The decisions for analysis were the following:

a) The observation grids would be analysed numerically per code and per group of action in order to investigate (i) whether there was a shift in teaching practices over time, and (ii) how the students responded to teaching practices. Numerical analysis would be done by observing frequencies of codes (how often a code occurred during a lesson).

b) Acknowledging that during the observations in the classroom we did not capture every single occurrence, we would transcribe and code the video and audio data to qualitatively record descriptions of teaching practices that enhanced critical thinking. Similarly, from the transcriptions and the coding we would highlight the student responses or initiatives that related to critical thinking occurrences.

c) From the student questionnaire, we would transcribe and look for student self-expression regarding their views on chemistry, their perception of self-performance and the relevance of classroom chemistry in their activities outside the classroom.

d) Finally, the teacher interviews and observer's reflective notes were used to collect data regarding teacher views about critical thinking in general, CT as a practice to the teacher's everyday life, and CT as a teaching practice. The aim of collecting this type of data was to establish what teachers thought about critical thinking within and outside the education context and examine if these views affected the expressions of CT in the classrooms.

During the data collection, there were impressions of changes in classroom behaviour, which were more obvious than others, i.e. the frequency of explanations increased. To examine that in detail and find evidence for it, I transferred the observations to excel sheets (Picture 3) and recorded the frequencies for the 20 codes. Observing that the lesson durations per cohort and among cohorts was not consistent, I opted to calculate percentage frequencies by dividing the numbers a code was recorded by the minutes the lesson lasted. For example from Picture 3, code 11 in Lesson 1 was recorded 25 times. The lesson lasted a total of 59 minutes. The percentage of frequency for code 11 for Lesson 1/Group 3 was 25/59 = 0.42. The percentages were calculated for all the lessons observed – classified per cohort.

	Obs	Obs	Obs	EM	Obs	EM
	22.02.16/L1	25.02.16/L2	29.02.16/L3	29.02.16	2.03.16/L4	2.03.16
0	11	11	11	11	11	11
1	11	11	11	11	11	11
2	11	11	11	11	11	11
3	11	11	11	11	11	11
4	11	11	11	11	5,11,11,10	11
5	5, 11	11	11	11	9,10,9,10	5.1
6	11	11	11	11	11.11	7,10*
7	5, 11	5, 11	11	11	11, banter	8a,2
8	5 (St)	4 , 3	11	11, 5, 11	8e*,8c*	3,8a,10*,2
9	5 (St)	6, 2, 2, 6	5,11	5, 11,5, 11	8c*	3,11,10*,2,7
10	11, 4, 3	3, 8c*, 10	10, 10*	11, 11, 10*	9,10,9,6a,6a	2,10,3,6
11	3	2, 6a	R	8a, 8a, 7, 8a	3/6,3/6,3/6	2,9,3,6,2,3,6
12	8a[1]	6a	R	7, 11, 10*, 7		10*,3
13	11, 11	6a	R	7, 3/6, 7, 6, 5		3,6,7,8e*,10*
14	11, 8	6a, 3-6, 3-6	R	4,2, 7, 8c*, 3, 7, 6		7,8e*
15	3 (ex.), 6	3/6	R	3, 8a, 6, 3, 8a, 11		7,8e*,10*
16	3 (ex.), 6	5, 10	3, 6, 6, 6, 6	8e*, 3/6, 6, 3/6		8a,8a*,7,8e*,2
17	3, 6	5	11, 3, 6, 3, 6	3/6, 7, 6, 7	8e*	7,8a*,2
18	4 (rev.)	5, 11	3/6	3/6, 2, 1, 6, 9		8a,3,9,10*,7
19	3, 6a[2], 8b[3]	11	11, 11	9, 3/6, 3/6		10*,8a*
20	3*1, 6	11	8e*, 11	11, 5/4, 5, 7, 8e, 8e*	11,8e*	8a*,7
21	3, 6	5	8e*	8e*, 8e, 8a, 8a		7,8a*,8e*,3/6
22	5	10*, 8d	7 (!), 8a*	3/6, 3/6		7,8e*,10*,8a
23	TT	10*, 8d	3, 2, 8c, 8c*	3/6, 1, 2, 6		7,8e*,3,8a*
24	TT, 11	10*, 8d	5, 4/5, 5, 5	4/5, 6, 7, 5	8a*	8a*,8c,8a,7
25	11 while writing in NB	10*, 8d	5, 5, 8a, 8b, 5, 3-6	5	8e*,8a*	8e*,7
26	3, 6, 4/5*2	10*, 8d	3-6, 5, 5, 5	8a,8b,2,5,8b,3/6,8a,8b	4(change of T)	7,11,8e,8a,3,6
27	11, 4*3	10*, 8d	8b, 8b, 5, 5	3/6, 8b, 7, 11, 5	4,3/6,8c*,8c*,10	4,3,6
28	5	10*, 8d	5, 5, 5	5, 10, 10*	4,8c*,8c*	3,6,4,3,9,6,4
29	3, 6, 1	10*, 8d	11 (experiment preps)	10*, 11, 3,7,8a,8b	4,8c*,3/6	6,2,1,4
30	3, 6, 11	10*, 8d	11, 5	10*,11, 8a, 7,5,6	4,3,9,10,9,10	4
31	5, 4, 8a*4	10*, 8d	10* prep4exp.	5, 7, 11, 7, 8e*	3,10*	4,3/5,10*,8e,8a
32	6, 10, 8b, 3, 6a, 3	10*, 8d	10* prep4exp.	7, 10*, 7, 8e, 8e*	3/6, discussion	8a,8e,8a*,4,7,10*,8e
33	9, 8a, 11	10*, 8d	10* prep4exp.	7, 8e, 8e*, 8b	3/6, discussion	8e,2,3,6,8a,8b,2/4
34	11, 3, 6 (1) , re-3, 6 (2)	10*, 8d	Experiments start, 10*	10*, 5/3/2, 8a, 8b	3/6, discussion	2/4,8a,8b
35	5, 4, 11, 4	10*, 8d	Experiments start, 10*	8e*, 8e, 7,8e, 10*	3/6, discussion	2/4,8e,7,8a,2,8e
36	4, 11, 6	10*, 8d	R, 8d	8e*, 8e, 7,8a, 5,7,8a	3/6, discussion	8e,7,8a,2,8b,6,7
37	4, 5, 3, 6, 3, 6	10*, 8d	R, 8d	8a,5,7,7,8e,8e*,8a	3/6, discussion	8b,6,7,5
38	3, 6, 3, 6	10*, 8d	R, 8d	7,8a,8e,8e*,10*	3/6, discussion	5,10*
39	4, 4	10*, 8d	R, 8d	8e,8a,8e*,7,3/4,8a	11,11,11,5 (change of T)	10*
40	9	10*, 8d	R, 8d	8e,7,8e*, 10*	Experiment prep	10*
41	4, 8a	10*, 8d	R, 8d	8e*,7,10*,8a,3/6	Experiment prep,11,11	10*,11,7,8a
42	TT , 3, 6	10*, 8d	R, 8d	8e,7,10*,8a,3/6,3	Experiment prep,11,11	8a,8b,10*
43	T gives explanation	10*, 8d	R, 8d	8e*,10*,7,8e*,8e	10.11	3,6,7,3,6,7
44	3, 6, 3, 6, 3, 6	10*, 8d	R, 8d	7,8e,10*,5	11,11,10	8a,7,4,3,6
45	3, 6	10*, 8d	R, 8d	5,8b,8e,7,11,10,5	11,10,7	8c*,10*,7,8b,8e*
46	3, 6	10*	R, 8d	5,8d,6,7,5,8e	11,10,5	7,8e*,10*,3/4
47	4	10*, 10	R, 8d	8d,7,8e*,7,5	11,10,5	8c*,3,6,3,6,7,3,10*
48	3, 6*5	3-6, 3-6, 4	R, 8d	8d,8e*,7,10*,7	11,10,5	7,3,10*,11,7,8e*
49	11, 3, 11, 6	3-6, 4	R, 8d	8d,7,8e*,8a,10*		5,7,8d,8e,11
50	7, 3, 8 , 11	3-6, 3-6, 8c*, 8c*	R, 8d	5,8e*,7,8a,8b,8e	8 of some kind	5,8e,7,6,7,10*
51	1	3-6, 3-6, 8c*, 8c*	R, 8d	8e,7,8b,8e*		7,10*,7,7,3
52	8	4	R, 8d	7,8e*,10*,5,11	Exp. Finished	4,3,6,7,3,6,5
53	TT , 11	2	R, 8d	3,7,8e*,11	11,11 Ss settling	10*,7,5,10*,11
54	TT , 8a	11, 11, 10	R, 8d	11,8e*,7,5,8e*	5	5/4,10,6
55	TT , 3, 6, 8b	11, 11	R, 8d	8e*,3,11	3/6	7,3,6,7,3,6/9
56	TT	q-aires	R, 8d	11,8d,3,7	4,3/6,11,10	2/3,6,7,8e
57	11 (packing up)	- 〃 -	R, 8d	3/6,3/6,2,7,8a,8b	8e*,5/3,4/3	3/2,5,4/5,7
58	11 (- 〃 -)	6, 8c*, 3-6, 3-6	R, 8d	3,8b,6,2,3/6,7,9	8e*,11	3/4,7,3,9/6
59	11 (- 〃 -)		R, 8d	3/6,7,8e*,3/6,3/6,8a	11	10*,8b,2/4,10*

Picture 3: Observations data from Group 3

Few bar charts for codes of interest were generated to have a visual comparison of codes from lesson to lesson. At this stage, a cleaning of data ensued. From the original 20 codes, the analysis focused on the 10 that provided information about questions, explanations, arguments and interactions that were relevant to these three elements. The quantifiable analysis started with codes 3, 6, 7 and 8a but it was obvious that the graphs did not yield satisfactory tendencies of the codes for interpretations in terms of teaching and learning practices. That quickly led to two actions: at first transcriptions of the video and audio records were created with annotations using the codes from the observation grid. Secondly, the lessons that had Obs and EM records were analysed to discover the sturdiness of the coding. The results of the analysis of the EM and Obs observations have already been presented (Section 4.3.4). The transcriptions of the videos provided clearer descriptions of deep and shallow questions and explanations and whether there was potential for the development of arguments.

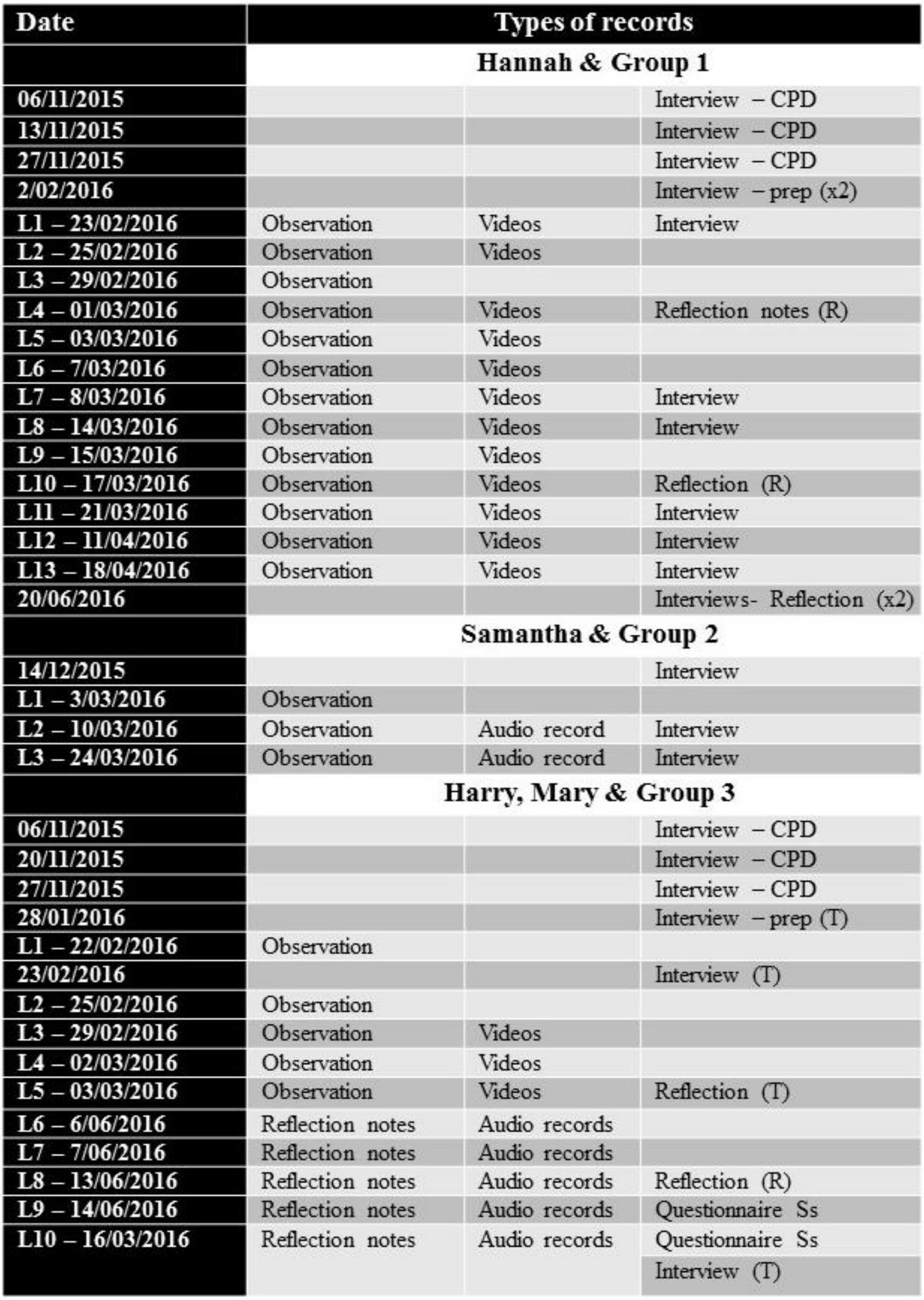
In more analysis of the qualitative data from dialogues in the classroom, I recorded the circumstances under which positive examples occurred, how frequent these occurrences and the overall lesson structures that fostered these occurrences. For example, in the interaction below the students worked on an exercise for electron configuration of two ions and reached a conclusion in the end:

> S20: Let’s just say -
> S18: It’s just easier for this one to move.
> S19 writes on her white board the atomic model for Fluorine using dots in orbitals [F=2, 7] then adds an extra electron [7 dots – one x] thus creating an ion.
> S20: Oh, it’s too complicated.
> Obs: Can you write it down?
> S20: I’ll write it. What should I write?
> S19: Lithium! It’s easier for Li to lose and atom, instead of gaining 7, whereas it’s easier for Fluorine to gain one atom, than lose 7.

Through the attempts to understand and depict the exchange of electrons between Li and F, S19 was able to explain how the exchange happens between the two elements and offer justification for this exchange according to her understanding. This interaction was annotated as code 8c (students providing information/explanation after encouragement) despite the mistake of refereeing to the electron as atom. I also noted the occasions that opportunities for critical thinking were missed with the intention of adding to the findings classroom practices that did not have a positive impact to the study objectives. The analysis of the video data offered more consistent measurements of the frequencies of occurrence for Qs, Es and As especially those that the students gave. From the video analysis, the factors with significant impact for CT were identified to be teaching practices that established an encouraging classroom environment that fostered student interactions with a level of independence. Dialogical teaching practices attributed to this change when the teachers refrained from lecturing and handholding students and instead allowed for and encouraged peer interactions, collaborations on in-class tasks and homework.

The teacher interviews, researcher reflective notes, and student questionnaires were the last datasets to analyse. The preceded analysis of the observation grids and video/audio data had already translated to a structure of the results from the study, highlighting with satisfactory clarity the areas of the research that had positive results as well as those that had little or no effect towards critical thinking. Therefore, the analysis of the interviews and reflective notes served as points of reference in order to support decisions that the teachers had made during their participation to the study. The student questionnaire was used for detecting time-lapsing effects on student CT between Phases 1 and 2 for Group 3. In the analysis of the questionnaire, other interesting observations regarding student criticality emerged. Detailed analysis of the data follows in Chapter 5.

Table 15: Matrix of data gathered per Group



Date	Types of records		
	Hannah & Group 1		
06/11/2015			Interview – CPD
13/11/2015			Interview – CPD
27/11/2015			Interview – CPD
2/02/2016			Interview – prep (x2)
L1 – 23/02/2016	Observation	Videos	Interview
L2 – 25/02/2016	Observation	Videos	
L3 – 29/02/2016	Observation		
L4 – 01/03/2016	Observation	Videos	Reflection notes (R)
L5 – 03/03/2016	Observation	Videos	
L6 – 7/03/2016	Observation	Videos	
L7 – 8/03/2016	Observation	Videos	Interview
L8 – 14/03/2016	Observation	Videos	Interview
L9 – 15/03/2016	Observation	Videos	
L10 – 17/03/2016	Observation	Videos	Reflection (R)
L11 – 21/03/2016	Observation	Videos	Interview
L12 – 11/04/2016	Observation	Videos	Interview
L13 – 18/04/2016	Observation	Videos	Interview
20/06/2016			Interviews- Reflection (x2)
	Samantha & Group 2		
14/12/2015			Interview
L1 – 3/03/2016	Observation		
L2 – 10/03/2016	Observation	Audio record	Interview
L3 – 24/03/2016	Observation	Audio record	Interview
	Harry, Mary & Group 3		
06/11/2015			Interview – CPD
20/11/2015			Interview – CPD
27/11/2015			Interview – CPD
28/01/2016			Interview – prep (T)
L1 – 22/02/2016	Observation		
23/02/2016			Interview (T)
L2 – 25/02/2016	Observation		
L3 – 29/02/2016	Observation	Videos	
L4 – 02/03/2016	Observation	Videos	
L5 – 03/03/2016	Observation	Videos	Reflection (T)
L6 – 6/06/2016	Reflection notes	Audio records	
L7 – 7/06/2016	Reflection notes	Audio records	
L8 – 13/06/2016	Reflection notes	Audio records	Reflection (R)
L9 – 14/06/2016	Reflection notes	Audio records	Questionnaire Ss
L10 – 16/03/2016	Reflection notes	Audio records	Questionnaire Ss Interview (T)

Summary

This chapter attempted to present the reasoning of the methods and design for this study, combining theory with practical aspects of the study and the teaching profession. The ontological aspect focused on the tools available to conduct the study, the participants and their role in the methods used for the recording of the data, and the physical environment of school premises. Epistemologically, it attempted to illustrate how new knowledge was generated from an interpretivist perspective in understanding the difference of duty as a teacher and as a researcher on aspects of teaching and learning chemistry that could not be immediately observed and measured except through specific occurrences, interactions and behaviours. This latter goal will be addressed in the following chapters.

5.0 RESULTS

Chapter objective

In this chapter, the data are analysed to demonstrate the practicability of the research questions as posed in Chapter 3. As explained in section 4.3.2, the collection and analysis of the data were based on set codes that described interactions between students and between teacher and students. These codes will be used to provide quantifiable occurrences accompanied by quotes between students or student-teacher to demonstrate how changes in teaching and learning practices influenced the skills of question-posing, explaining scientific concepts and phenomena and occasionally arguing for or against explanations. Simultaneously, reference to teacher inputs, impressions, or reflections from interviews before or after the completion of lessons are presented to complement these discussions. The occurrences under discussion were efforts to gain more precise understanding of the interrelations of the three components – question, explanation, argument – as they were presented in Chapter 3. The analysis is compiled per finding and discussion of each group is compared and contrasted with the other groups with the aim to showcase the different ways critical thinking was practiced in classroom setting and the impact it had. Given that each teacher had a different approach to the study, there is exploration of what happened when CT was not integrated as a learning aim.

5.1 Data treatment and syllabus overview

The count of occurrences per observation sheets was not an objective measurement because the lessons did not have the same duration. To get an objective measurement that allowed for comparisons of different days and different groups, percentages were calculated for each code. Each percentage was calculated by dividing the number of occurrences recorded per lesson divided by the duration of the recorded lesson. This produced the weighted frequencies per code for comparison of interactions from lesson to lesson and from group to group. For all groups, graphs were generated using data recorded on the observation sheets and were juxtaposed against data from the video/audio records. The graphs helped to observe shift (or not) in the use for preferred teaching practices and their influence on classroom practices and were analysed in comparison and contrast to the qualitative data. They were further used to investigate whether observed peaks per code or in specific lessons with implemented lesson

CT-aimed plans had been successful, i.e. student-generated questions in Lesson 4, Group 1. The graphs for the teacher-related codes 3, 4, and 5, were generated using only observation sheets, whereas the student interactions, codes 6 to 8 (including sub-codes), accumulated occurrences from the observation sheets, video and audio recordings. Comparison of lesson plans with specific CT aims and specific designs against lesson observations are made in subsequent sections.

Before commencing the analysis of the data, an overview of the syllabus is necessary to frame the analysis, based on the ten codes that resulted from cleaning the data (section 4.3.3). Group 1 had the longest study and therefore presented the richest dataset. As it will be shown in the analysis sections below as well as in the discussion in Chapter 6, the data from this group offered valuable insights and interpretations, successful instances and opportunities for improving the conceptualisation of practices. There were 27 student participants in this group using the aliases S1 to S27 in the student quotes in the analysis. The chemistry content for Group 1 was the introduction of the atom and the exploration of atomic models over the centuries. The content was ideal for a study designed to influence students' critical thinking, because it offered opportunities for independent exploration and student research on atomic theories developed over time. The lesson series that Hannah planned for Group 1 is shown below:

Lesson 1: Change of the state of matter, the concepts of atom and molecule

Lesson 2: Atoms, Molecules, Compounds, the Periodic Table

Lesson 3: Evolution of the Atomic Theory, Part I (student research)

Lesson 4: Evolution of the Atomic Theory, Part II (student presentations)

Lesson 5: Physics, Chemistry, Biology … or Science?

Lesson 6: How mass and atomic number explain the atomic structure

Lesson 7: Patterns of the Periodic Table

Lesson 8: Electron Configuration

Lesson 9: Electron Configuration – Group 1

Lesson 10: Bonds and Bonding

Lesson 11: Ionic Bond

Lesson 12: Reactivity of Group 7 – Displacement Reactions

Lesson 13: van der Waals forces – Properties of Noble Gases

Group 2 had the smallest dataset due to the shortness of the study. The value of the observation data this group added to the study was not relevant to suggested teaching practices, as the teacher opted out of using them. However, the teacher outlook and attitude towards CT were a more substantial contribution. Teacher interviews offered an additional viewpoint of challenges teachers faced when encountering the concept of critical thinking, for themselves and their students. Fifteen students participated in this Group with the aliases N1 to N15. Similarly to Group 1, Group 2 was also learning about the atom and atomic theories early in the Spring term. Samantha explained that the lessons that followed after the Easter break were not relevant to the study as the expressed interest from the research focused on the atomic theory, which would be covered in 3 or 4 lessons before Easter. Samantha had a very clear compartmentalised view of the chemistry syllabus, which was apparent from this segmentation of lessons relevant to the study. School visits were planned purposefully to target specific content and the selection of topics that Samantha used for Group 2 are shown below:

Lesson 1: Introduction of atomic theory

Lesson 2: The Fire Cycle and Thermal Decomposition

Lesson 3: The Structure of the Earth

The Periodic Table, electron configuration and introduction to chemical reactions, were topics that Group 2 would explore in lessons following the Easter break after the last planned school visit.

For Group 3, the researcher-observer was often asked to participate in the lessons; assisting students while they were doing their experiments. Although that was an accepted practice, it affected the recording of observations. There were gaps in the observation sheets that the video records could not always cover. The non-recorded minutes were taken out of the overall duration of the lesson when weighted codes were calculated. The study with Group 3 was designed in two different phases, Phases 1 and 2, in Spring and Summer respectively, both investigating the Rate of Reaction. For the second cycle of observations with Group 3, the lessons the data collected focussed on discussions with teams, individual students, and the teacher in the fashion of reflections and the inferences from Phase 1. This provided an opportunity to observe the impact a time lapse had on student observations and critical skills. There were 26 student participants in this group with the aliases S31 to S326. The class visits with Group 3 were to observe the teaching and learning experience of the Rate of Reaction (RR) and implement practices that fostered the development of critical thinking for the students. The lesson plans were titled (according to AQA specification):

Lesson 1: Reactions and Collisions

Lesson 2: Factors that Affect a Reaction

Lesson 3: Concentration

Lesson 4: Surface Area

Lesson 5: Temperature and Catalyst

Though the philosophy of the study with Group 3 remained the same, using questions, explanations and arguments to foster CT opportunities, the collaboration with the teacher and trainee teacher for Group 3 was yet a different approach. Harry was confident from the Preliminary interviews that he was roughly using the proposed teaching approach in his chemistry classes already and he felt that the suggestions were not going beyond what he usually did.

> **Quote 1 – Preliminary Interview 2**
>
> Harry: I give them the conditions: low temperature-high temperature, more surface area-less surface area, higher concentration-lower concentration and then *I ask them to come up with a theory* about active particles. Can you explain then, the chemistry, if you know that there is collision between particles? They can kind of develop a collision theory model.

Harry had counter suggestions for the design of the study for Group 3, which were mostly related to the accuracy of methods used in school chemistry. Harry worried that the low-level apparatus that the school had access to, for instance not having a proper gas syringe to measure the gas emitted in a reaction affected students' performance. Specifically, the experiments under observation were related to three factors: (1) the concentration of an acid,

(2) the surface area of a solid reactant, (3) and the use or not of catalyst. The suggested practices proposed that (1) concentrations varied per team, (2) in terms of size of solid students had three options of which they could choose two, and (3) when temperature was under investigation, students could choose two out of four different temperatures.

In addition to the analysis of the codes, in subsequent sections, narratives per finding include illustrative examples of students' contributions in the lessons which were highlighted as products of critical thinking ("eureka moments": to borrow an expression from one of Mary's interviews) or instances where an opportunity for critical thinking was well- or badly-utilised. The choice of instances presented was based on the content and, therefore, the quoted text came from different students as per the recording during the lesson. The study did not focus on the progress of any individual student. It did not target a particularly weak or strong portion of student population. Critical thinking was viewed as a mind frame that all students could be given the chance to develop and therefore focusing on specific students would have taken attention away from observing the whole grop. However, justification was given when consistency of contributions from specific students was observed.

5.2 Analysis and Presentation of Data

The analysis that follows presents the data per finding in separate sections. Contributions from each group showed the way the components in the research questions were implemented and observed during the school visits. In relation to the research questions, suggested practices were discussed with the teacher participants. Teacher questions should aim to prompt student explanations frequently in order to normalise the practice in the lesson. The student explanations should progressively move away from citation to providing evidence in support of an action/interaction. Equally, prompting more student questions was desirable with a similar goal for progression from simple, factual, shallow questions to deeper, investigative, enigmatic questions. Arguments were expected to follow naturally from the momentum of students gaining confidence of expertise.

There were no preliminary observations of teachers and their groups prior to the first class visits, so the lessons of the first weeks – Lessons 1 and 2, for Group 1; Lesson 1, for Group 2; and Lessons 1 and 2, for Group 3 – served as a baseline for each study. This was a starting point for the researcher and teacher to reflect on and decide how to use the three elements (questions, explanations, and arguments) to enable development of critical thinking.

The major findings analysed in the rest of the chapter are listed below:

1) Frequency of teacher-generated questions affected critical thinking opportunities only when combined with content and purpose of Qs (Section 5.2.1)
2) Student-generated Q-E-As had a stronger element of E, good potential for A and less potential for Q. Not opting to use peer-questions did not impede showcasing CT (Section 5.2.2)
3) Teachers' beliefs and attitudes towards CT affected students' attitudes towards CT respectively and proportionately (Section 5.2.3)
4) Organisation of lessons targeting the enhancement or practice of a specific element (Q, E, A) had a positive outcome for the element (Section 5.2.4)
5) The implementation of in-class tasks (that included experiments as well as chemistry exercises, presentations, student research) with specific aims to engage students in investigation and peer interactions propelled the confidence of student to verbalise their thought process and improve explanations and CT.

In relation to the findings mentioned above, we have foreshadowed that questions were treated as the beginning of an investigation. The teacher role past the question was to encourage and invite student explanations, which was observed to be successful. In the analysis below, we will present data that favoured peer questions, for instance, when a lesson was constructed to foster this type of peer interactions. This was clearly affected by the teacher views on whether practices that encouraged peer Qs, Es or As were useful and contributing to the learning aims of the chemistry. Finally, in Section 5.2.5, we aim to present how the adaptation of classroom practices to the development of specific rapport, i.e. peer and student-teacher dialogue, improved the student-student and student-teacher interactions and the occurrences students expressed their thoughts revealing CT processes.

Having analysed the duality of chemistry as a science that requires a lot of action but also a lot of thinking, the way content was organised for Group 3 was opposite to that for the Year 9 studies. In Year 9, the lessons built from theory learning to practice aiming to populate knowledge building blocks that the students could apply when performing simple experiments.

The CT development went from thinking to doing and aimed to make theory more applicable in practice with pattern recognition and model building. On the other hand, the reasoning behind the suggested practices in Year 10 worked from practice to theory, compiling experimental data for conceptualisation of the Collision Theory. The teachers were explicitly instructed to provide basic knowledge blocks for Collision Theory prior to experiment. The different experiment settings leading to discrepancies in results per experiment aimed to propel communication and collaboration across teams to debate tendencies and discuss practical – obvious – differences in experimental processes. Both designs wishfully would steer students to build their own theoretical explanations about the reasons for the observed differences, compile evidence collaboratively, and promote peer questions, explanations and arguments towards theory building. The experiments were easy and straightforward to allow time for discussion and reflection.

5.2.1 Teacher questions: significance of frequency and content

From the pilot study, the observation was that the teachers often asked too many questions that required one-word answers. These quick and frequent teacher-student interactions occurred several times per lesson and were viewed as shallow questions that took up valuable time and inhibited opportunities for deeper questions. Therefore, the original research proposal was for teachers to ask fewer questions and rather focus on investigative questions. This, however, did not have the expected outcome.

For Group 1, the teacher did not reduce the number of questions she asked, rather the number of students she asked the questions to. Hannah’s practice shifted from asking quick and frequent questions to the class to asking task-related questions per sub-group, which had a positive effect in content of student answers. Overall, observing the teacher, the number of questions did not reduce, but the audience was smaller and the questions better tailored to the audience.

For group 2, Samantha had a consistently high number of questions in her teaching practice from which she did not deviate during the study. She frequently repeated her questions during the lesson and answered them herself before she finally expected an answer from the students. This practice did not leave much opportunity for student development in critical thinking. We cannot speculate how the frequency of questions might have changed the student response, had Samantha adopted any proposed adjustment.

The teaching team of Group 3 were the most successful in reducing the number of questions and the amount of lecture-type teaching of the three. The overall observation of this practice was that the lack of teacher questions regarding student rationale for action and theory had an adverse effect on opportunities to practice critical thinking.

More specifically, Hannah, for instance, did not reduce the number of questions she asked over the period of the study (Table 16). In fact, from Lesson 1 to Lesson 11, the teacher-generated questions increased in frequency (Figure 13). Despite the original assumption that this was an inhibiting practice, it turned out that the high number of questions was not necessarily depriving students of time to develop critical thinking. On the contrary, Hannah created opportunities for critical thinking using collaborative activities, such as presentations, fact files – a suggestion of Hannah's – in-class tasks, and research-based homework. In this practice, the teacher questions shifted to being task-based and task-related and created conditions for the formation of small groups and collaborative work. Hannah had the opportunity to walk around the class and ask each group to discuss their thinking process and task progress for her. The occurrences of Hannah walking around the class and engaging in Q&A with each group, were frequent enough to consider it a new teaching practice (references from Obs reflective notes, Table 17).

Table 16: Number of teacher-generated questions per lesson, Group 1

Group 1	**L1**	**L2**	**L3**	**L4**	**L5**	**L6**	**L7**	**L8**	**L9**	**L10**	**L11**	**12**	**13**
No of Qs	24	19	25	30	27	58	37	45	49	41	55	31	43
Average	37.23												
Lesson Duration	58	59	57	57	24	57	56	59	55	54	64	62	64
Average	55.85												

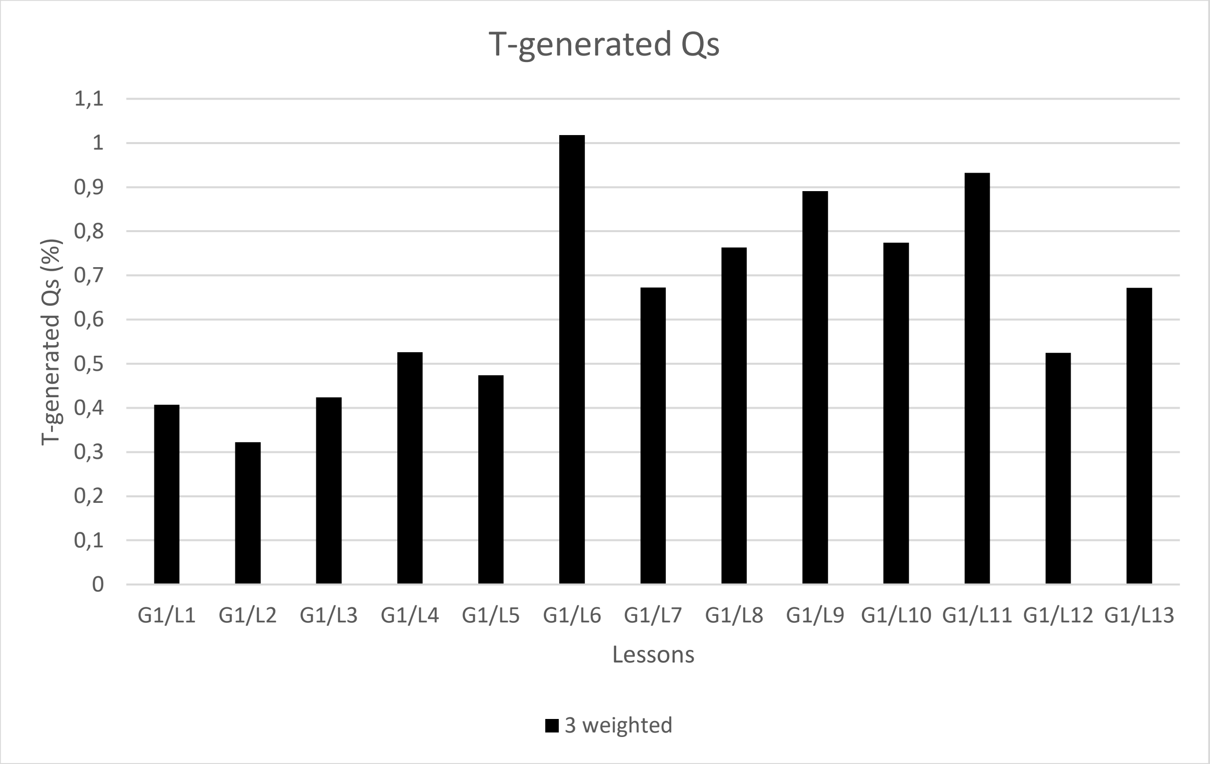


Figure 13: Weighted frequencies of teacher-generated questions

Table 17: Observer's reflective notes on Hannah's actions during the in-class activities

G1/L1 Change of the state of matter, the concepts of atom and molecule
Min 32: T walked around asking a Q to all students. Ss provided multiple answers. They all seemed like the wanted to answer for themselves.
G1/L2 Evolution of the Atomic Theory – Part I (Ss research)
Min 36 onwards: T went around again and asked how Ss were going to present in the following lesson.
G1/L6 How mass and atomic number explain the atomic structure
Min 23-24: T walked around and asked Qs to help Ss get to the answers
G1/L7 Patterns of the Periodic Table
Min 36: T was looking for an answer for a Q from the previous lesson. Chlorine and Copper have decimals in their atomic weight - why? T walked around and asked Ss to help each other with the completion of the exercise
G1/L8 Electron Configuration
Min 25: T walked around and tried to help Ss annswer by asking them Qs
G1/L10 Bonds and bonding
Min 46-53: T asked Ss to balance equations of alkali reacting with wather (codes 3/6). T was walking around and helping Ss work out their equations. During that time Ss had stopped recording the lesson in videos
G1/L11 Ionic Bonding

Min 9: T was walking around while Ss were trying to work out the floride ion F-. T asked Qs to help Ss solve the problem
Min 18: T walked around asking Qs and encouraging Ss thinking/reasoning about the formation of ions
G1/L12 Reactivity of Group 7 - Displacement Reactions
Min 29 - end: T walked around and tried to help Ss find the explanation for the reactivity of Group 7
G1/L13 van der Vaals forces - Properties of the Noble Gases
Min 48: T goes around and encourages Ss' work by asking qs
Min 52: T goes around and encourages Ss' work by asking qs
Min 60: Teacher prompts answers: "because…?"

The original assumption was that fewer teacher questions would allow for more student response time, i.e. the questions ought to motivate students to think before they provided an answer and in that context fewer question made sense. Hannah’s practice of changing from questions addressed to the whole class into questions addressed to sub- groups, kept the number of questions roughly the same. However, if a question required reflection and combination of information for an explanation or argument, that motivated students to examine their data and actions closer, discuss and collaborate to provide an answer, assist each other’s understanding. Most importantly, Hannah did change the type of questions from shallow to more explorative (Quotes 2-5), and spending time with each group meant that the number of teacher questions per lesson remained overall stable and relatively high for the duration of the study. In Quote 2, Hannah’s questions required either a single-word reply or recollection of prior experience. In Line 12, for instance, she did ask students to justify an answer, but the information she asked for was again a repetition of what students had practiced in a previous lesson. It did not require thought or understanding of the why.

Quote 2 – Lesson 1 – examples of shallow questions (my italics)

Hannah: *What is stuff made up of?*
Students: “Atom,” “Cells,”
S2: Atoms, molecules and cells
S21: Particles
Hannah: Particles indeed.
Students: “Matter,” “Solid,” “Gas”
[…]

> Teacher giving instructions about the experiment of burning an Mg strip using Bunsen burners. Hannah: *What's gonna happen?* You've done it before.
> S21: Blue light, uh, white light
> Hannah: A white light. *Are we gonna be staring at it?*
> Many students: Noooo
> Hannah: *Why? What might happen?* (**Line 12**)
> Many students together say it will hurt their eyes, they might go blind.
> Hannah: You can blind yourself. (Teacher goes on to give detailed instruction).

Quote 3 – Lesson 5

> Hannah draws the models of the Greeks and Dalton to show the similarities – solid ball that cannot be split – then asks;
> Hannah: But how did he [Dalton] develop the idea of the Greeks?

Quote 4 – Lesson 6

> Hannah (to class): Could you go back to that diagram that you're explaining, is there anything that you would say differently to the people on your table about the structure of the atom? Is there anything you've learnt that you can now verbalise to people at your table?
> […]
> Hannah (with a small group): What do you think the simplest element is? S9?
> S9: Hydrogen.
> Hannah: Why?

Quote 5 – Lesson 8

> Hannah approaches a small group: What are we doing, S17?

Progressively, the teacher's questions became more profound: "But how did he develop the idea from the Greeks?" was a question that required reflection more than recollection, because it asked the students to connect two points of evolution in the atomic theory that she or the textbook had not taught them beforehand. By Lesson 8, the teacher asked students to describe their work and thought process more frequently than using questions for fact checking. Hannah reflected on her question practice after the first lesson about the type of change she wished to implement in accordance to the research aims (Quote 6). She got progressively accustomed to asking her students questions of exploration and investigation, in essence asking them to contribute answers that evolved both their speaking and thinking.

Quote 6 – Interview from Lesson 1

> Researcher: I don’t expect them to be able to say, you know, electrons jump from one shell to the next and that’s why we see the light and everything. But if you can ask them to give an explanation – and by that I mean description plus ‘what do you think?’ (my italics).
>
> […]
>
> Hannah: So I was very aware […] that *I shouldn’t be giving them all the right answers*. And when they were modelling in the end that some of them had very different ideas and some of them had definitely got it. But I am not convinced that they were sure about what – But then this is starting point, isn’t it? This is them starting this chemistry module where, yes, *they have done the experiment before but do they know* what is happening with those atoms?

Samantha, similarly asked questions at high frequency as a usual teaching practice (Table 18). However, Samantha’s practice did not have a positive effect on students’ opportunities for critical thinking (Quote 7). From the numbers in the table below and the teaching practice portrayed in the quote, most frequently Samantha asked questions that she did not expect students to answer. Analysing the quote, her practice was heavily based on repetition. She presenting new content to the students, provided lengthy and repeated explanations. Then she asked questions, which she replied to immediately. The questions she did expect students to reply to she eventually asked only after asking and answering the same questions several times herself. The repetitive pattern served for memorisation of the answer by the students and it was not thought-provoking enough.

Table 18: Number of teacher-generated questions per lesson, Group 2

	G2/L1	G2/L2	G2/L3
Number of questions	39	31	57
Average	42.33		
Lesson Duration	45	49	52
Average	48.67		

Quote 7 – Lesson 2

> Samantha: [teaching the fire triangle] You can say fuels. We call those fuels and … oxygen. Oxygen is a really good word. And what is missing is heat but we are going to go through that in a second. So this is what you’re going to be describing today. We are

> going to learn that Oxygen combined with heat and fuel makes a chemical reaction and we're going to write down word equations, OK? So, I'm going to give out a paper.
>
> Teacher gives the handouts to students.
>
> Samantha: So firemen use this [fire triangle] so it is called the combustion triangle. So you've got on your sheet, in your book a proper combustion triangle. And it's called the combustion triangle because it has on its peaks all the things that are necessary. Can you see on your combustion triangles what three ingredients are needed for combustion to occur? The second thing is what is combustion. Can you write in that line what three things are needed? What three things are really important? So what three things are needed for combustion to occur? Oxygen, heat, and fuel. So these are the three things that needed for fire and combustion is another word for burning. So combustion is another name for that. And also it is an example of an exothermic reaction, which means it releases energy to the environment. Does anybody know what is an exothermic reaction? Have you come across it? It is a big word. So it's when heat is given off in the environment. So when heat is created in a combustion reaction and it is given off in the environment. So combustion is another word for burning. You want to write that down, what is combustion? It is another name for burning. It is another name for burning. So, do you know what is combustion S5?
>
> N5: It is another word for burning.
>
> T: And what are the three things that are needed?
>
> N5: Oxygen, heat, and um, fuel.

This teaching practice gave high frequency of questions from the teacher not accompanied, however, by an equally high-level contribution from the students mostly due to restriction of question content opportunities for responses.

Data from Group 3 showed yet a different approach and outcome to the use of teacher questions. Harry and Mary asked overall fewer questions per lesson, in comparison to the other teacher participants (Table 19). This corresponded to the research instructions for fewer questions in order to provide students with more time to reflect and theorise. In practice, however, when Mary was in charge of the lesson, her questions were more often repetitive and related to process. She often missed creating opportunities for reflection, i.e. asking questions like 'what did you observe from the previous lessons? What did you understand? What is your impression?'. Lessons 3, 4 and 5 were based on experiments, occasioning frequency of questions – teacher and student. However, Harry had preconceived ideas for the practical part of the study (Quote 1). He would not necessarily ask questions but he would ask his students to contribute their views. Mary, on the other hand, needed more support and further input in order to successfully implement practices that built up exchange of student ideas (Quote 8).

Table 19: Number of teacher-generated questions per lesson, Group 3

Group 3	L1	L2	L3	L4	L5
No of Qs	30	14	7	17	10
Average	15.60				
Lesson Duration	59	58	33	59	28
Average	47.40				

Quote 8 – Preliminary Interview for Mary

> Mary: I had an idea about the concentration experiment. To ask them to draw for example what the particles look like in a 0.1M solution and what they look like in a 0.5M solution to see if they understand the idea of more concentration and how it affects the rate of reaction.
>
> Harry: I would give them less than that. I would give them key words like collisions, successful collisions, unsuccessful collisions, particles, likelihood and tell them to come up with something using those words. If we taught as we normally teach, we would give all of that away. We don't want to give much input at all, if anything we are dramatically reducing the amount of talking that we do. We are going to be very selective. We are going to be different in our teaching styles for those few lessons.
>
> […]
>
> Mary: I talk a lot
>
> Harry: They will have maybe half an hour for the investigation and then we need to leave time –
>
> Mary: For them to think about it.
>
> […]
>
> Mary: Do you want us to tell them 'go home and think about that and come back…'
>
> Researcher: Yes, do tell them that. Encourage them to think. Encourage them to reflect, to do reflective thinking.

Harry's approach was based on asking students to actively produce something in way of doing or thinking. He organised experiments for hands-on experience but he also followed up the experience with a thinking exercise. Although he realised that it was crucial to provide students with time to think, this did not work so well. From the three experimental lessons, students were invited to engage in reflective discussions once. Though Harry's practice was viewed favourably (section 5.2.3), borrowing from the potential of Hannah's practice, it is arguable that more questions might have been helpful for more favourable results.

Mary was comfortable being the questioner. Her questions, however, were mostly procedural and factual not leading to reflective discussion and propelling thinking (Note 1 and

Quote 9). On the occasion that she did encourage students to reflect on what they had done and observed from two experiments, the student response was not favourable (Quote 10).

Note 1 – Lesson 1

Min 36: Mary asks "Do you know Reni tablet?" [tablets for stomach burns] Mary explains how the tablets are alkalis and they neutralise the stomach acids' function, thus taking the burn. INSTEAD she could ASK the students to find out – with the knowledge they have what happens in the chemistry level.

Min 42: Mary asks a lot of one-word-answer questions.

Min 43: Mary gives explanation instead of asking students to use their knowledge of neutralisations to understand how Reni tablets work.

Quote 9 – Lesson 3

Mary: How's it going?

S33: Nothing.

Mary: Did you read the instructions?

S32: Yes.

Mary: Did you follow the instructions?

S31, S32 and S33: Yes. (short pause)

Mary: Try it again.

Quote 10 – Lesson 4

Mary: Think about the change of the mass that we are observing. Right, on that graph, rate of reaction is that line on that graph. Rate of reaction is how quickly it changes, OK. It's how quickly something changes. *So, which one has changed more quickly*? So we have seven results on one side. We will compare with the seven results on the other side.

S35: Is it smaller?

Mary: Which one has changed faster?

Some students say the smaller chips, some students say the larger.

Mary: So which one has the quicker rate of reaction?

The answers are again not unanimous.

Mary: Look at the difference between that and that [left column, values 1 to 7] and between that and that [right column, values 1 to 7].

S315: I'm confused. I'm not even learning anything in this entire lesson.

S322: Basically, that one is higher than that one.

S315: I wouldn't know because I wasn't here in this entire lesson learning.

Mary: So, what you're going to do is, you're going to think – so we had the small ones and we had the large ones [chips]. And you guys are going to go away and you are going to think about this [showing the slide with the two boxes about collisions and successful

> collisions] and you are going to explain the rate of reaction in terms of particle size. *So, go home, think about.*
> S315: Yeah, "go home and think about it" [in ironic tone].

Mary's question regarding the solution that reacted more quickly was an appropriate initiator to guide students to look at the data holistically and start synthesising an impression. Her question went a bit further than that when she comparatively referred to the size of the chips in relation to the rate of the reaction. She could have started a classroom debate where her students could have argued for one or the other point of view until the discussion stirred to more evidence. However, it was obvious from the student reaction that more teacher input was necessary for the classroom discussion/debate to occur. The lesson was nearing the end as well and there was not enough space for reflection to help students grasp the concept the teacher was trying to scavenge. Evidence of this is obvious from S315's comment of irony.

From the data generated in the three groups, positive outcomes were identified when students had the chance to verbalise coherent views and presented their thinking devices in some way. These were usually responses to deep teacher questions or occasionally peer interactions and brought content and justification to focus. For instance, in Quotes 3, 4, and 5, Hannah asked her students to share their work with her, giving them opportunity and time to present their thoughts and thought outcomes. In Lesson 4 specifically, all students presented findings on important historical figures and their work in a historical timeline of the Atomic Theory. Hannah's questions in that lesson were consistently guiding students to think about the information and collate it with what they already knew (Quote 11). By posing four key questions (who, when, what, how) as anchors for information retention per presentation, Hannah set a rhythm for her students to follow in the lesson.

Quote 11 – Lesson 4

> Hannah: Now, remember you're writing notes and try to answer as many of those points [when, who, what] as possible but also be thinking '*How does it link to what my model is*?'(my italics).
> […]
> Hannah: So think of the time gap between, what year were you guys, 400BC? […] From 400BC to 1804. That's a good amount of time, isn't it?
> […]
> Hannah: So same volume, same temperature. *Why temperature? What does temperature do to particles?*

> […]
> Hannah: What they were? What happens to the stuff inside that tube? It’s a…
> S11: It’ a vacuum.
> Hannah: And what do we use a vacuum for?
> S11: To stop that particle.

The teacher questions required justification of the information presented.

Samantha also asked a few intriguing questions to her students (Quotes 7 and 12). However, she did not give the students enough time and opportunity to recollect or think or reply to the questions. When the questions she asked required further information, scavenging prior student knowledge perhaps, she did not follow up with further supportive questions or information, rather she quickly provided the answer. We could not really tell whether the students were able to reply to the questions or not, as the teacher provided the answer too quickly.

> **From Quote 7 – Lesson 2**
>
> Samantha: So combustion is another name for that. And also it is an example of an exothermic reaction, which means it releases energy to the environment. *Does anybody know what is an exothermic reaction*? Have you come across it? It is a big word. (my italics)

> **Quote 12 – Lesson 2**
>
> Samantha: *How can we plan an investigation to test that the products of combustion are carbon dioxide and water*? So we have got a word equation here to show the chemical reaction. So what we have on this end is our fuel and we’ve got Oxygen and we have water and carbon dioxide produced. Our products for the chemical reaction are what S14? What are the products for the chemical reaction?
> S14: I don’t know.
> T: You don’t know? OK, S2?
> S2: Water and carbon dioxide.
> T: Water and carbon dioxide, yes. *How do we know these are the products*? (my italics).

Defining the exothermic reaction was not an easy task and engaging the students to discovering and describing what it was, i.e. by giving examples, offered opportunities for pattern recognition, reflection, the consolidation of an explanation.

Harry and Mary also had few examples of questions that meant to propel students' thinking and give a chance for observations and combination of information. The key difference to Samantha's practice was that Mary (and Harry) allowed time and occasionally followed up with further questions or prompts to help students both come to an understanding as well as verbalise it (Quotes 13 and 14). Mary (and Harry) tried to practice CT boosters in the lessons and had positive attitude towards it, whereas Samantha could not see the value of it for her students.

Quote 13 – Lesson 4

> Harry: So, put your hand up if you can tell me, anything really any idea you may have as to *why there is such a variety of results and maybe why they didn't follow the trend that we were expecting*. Only with your hands up. S318?
>
> S318: Because the substances that we put did not have the right amount?
>
> Harry: Possibly, yeah. It might have been that you diluted them wrong. That could be one factor. S323?
>
> S323: Is it the water? Just adding more water made a difference?
>
> Harry: Yes, the ones that were water and we tricked you with, sorry S32. We wanted to see if you could guess what was happening and what had gone wrong. So in that reaction there was never going to be any time that the thing changes colour. So we had this point (showing the lowest point on the graph) which took longer. So that's another factor. What else? S35?
>
> S35: People stopped the timer at the wrong point because they thought they could not see the X.
>
> Harry: Very good. That could be the most important factor in this experiment completely. Because this changes so slowly, this colour change, people may have stopped it when they first saw the little bit of colour appearing or you may have stopped it exactly spot-on when it did disappear, or you may have spotted well after it had disappeared. (my italics)

Quote 14 – Lesson 4

> S314: The more concentrated the acid is the slower the rate of reaction occurs.
>
> Mary: *Is that what we saw*?
>
> S36: I think it's faster.
>
> Mary: *Why do you think it is faster*?
>
> S36: We had 18 acid and it was the fastest rate of reaction.
>
> Mary: *Ah! Evidence*.
>
> S37: It was the longest.
>
> Mary: Remember I drew the beakers on board? (draws on board). Just to refresh our memory.
>
> […]

> Mary: Now you have a visual representation of what was added. Which one of those – *we had a few contrasting opinions*. So, who thinks that one [lower concentration] made the rate of reaction faster?
> Students hesitate.
> Mary: Who thinks that one made the rate of reaction faster [higher concentration]?
> Some students raise their hands.
> Mary: *Have you got your results written down*? (my italics).

In Lesson 4, when Group 3 spent twenty minutes of the lesson reflecting on the concentration experiment and the results the teams had produced, both Mary and Harry asked and probed students enough to get them to express their views with positive results. These were model questions and prompts that facilitated critical thinking.

5.2.2 Student-led interactions: frequency and content of questions, explanations and arguments

In total, seven codes were analysed involving students: two codes described student-teacher interactions and five peer interactions. The codes for student-teacher interactions were code 6 – student replies to teacher questions; and code 8a – when students posed questions to the teacher. The codes for peer interactions were code 7 – replies to peer questions; code 8c – student-generated explanations, ideas, information; code 8c* – same as code 8c but with encouragement from the teacher; code 8e – peer questions; and code 8e* – miscellaneous peer interactions that did not fall into any of the other categories. From those seven codes, students were expected to be comfortable with the student-teacher interactions as they were a traditional type of student-teacher dynamic: teachers always ask questions and expect answers with varied purposes, and students often ask questions to the teachers to get or verify information.

Peer interactions included peer questions, explanations students exchanged during their group work, discussions during in-class activities, comments, corrections and ideas. Certain lessons aimed to promote one specific CT skill. For instance, the design of Lesson 4 with Group 1 meant to engage students in peer Q&A and the teacher took care to adopt a teaching practice that aided that. All the experimental lessons for Group 3 (Lessons 3, 4, and 5) and the yield of different results from different teams were specifically conceptualised to create the circumstances for peer interactions, exchange of data and procedure information, promotion of discussion and debate. With Group 2, there were not any opportunities for the study to influence the lesson planning or delivery and the classroom habits did not encourage peer interactions. Therefore, the references from the dataset of Group 2 highlighted mostly potential the students showed.

5.2.2.1 Peer and Student-teacher questions

In the pilot study and the theoretical analysis student-generated questions meant to signify a starting point for verbalising the thinking process, therefore they were viewed as very important. In the study and with the collaboration of the teachers, emphasis was placed on the notion that the classroom practice should encourage students to ask questions to their teachers but more so to their peers. The ambition within the study was that student questions to the teacher would change from looking for confirmation of knowledge already learned to asking the teacher exploratory questions to complement their understanding with new knowledge. Ideally, student questions to the teachers would be looking for direction to new content, further knowledge, better understanding. In Group 1, the observations and video data recorded this shift, and less so for the other two groups.

From the graphs of the three groups below, the numerical data showed moderate preference for students to ask questions which was more pronounced for questions directed to the teachers (Figure 14, graphs A, B, and C). The qualitative data also showed that students had the tendency to ask questions to the teachers frequently and with ease, but they were not particularly interested to ask questions to their peers (quotes). During the analysis, the focus was originally on peer questions, and later followed analysis for student-teacher questions (and the same order of analysis follows in this section).

In regards to peer questions, the overall observation was that peer questions were not the preferred type of communication, unless the lesson design focused specifically on encouraging them with plenty reminding from the teachers so that the students participated in peer Q&A. Much like the student-teacher questions, with peer questions the aim was for questions to move from shallow to deep. *Peer* deep questions would reveal spontaneous reflection on content, combination of information, and individual achievement of the critical thinker while missing the performance anxiety of asking and answering in front of the whole class. Peer questions did not occur naturally within the lessons; they were usually the result of teacher encouragement. The exception was the experimental context, but even then most peer questions were procedural, and therefore shallow in nature. Peer deep questions were not recorded. The study relied on explanation criteria for critical thinking encouraged among peers (section 5.2.2.2).

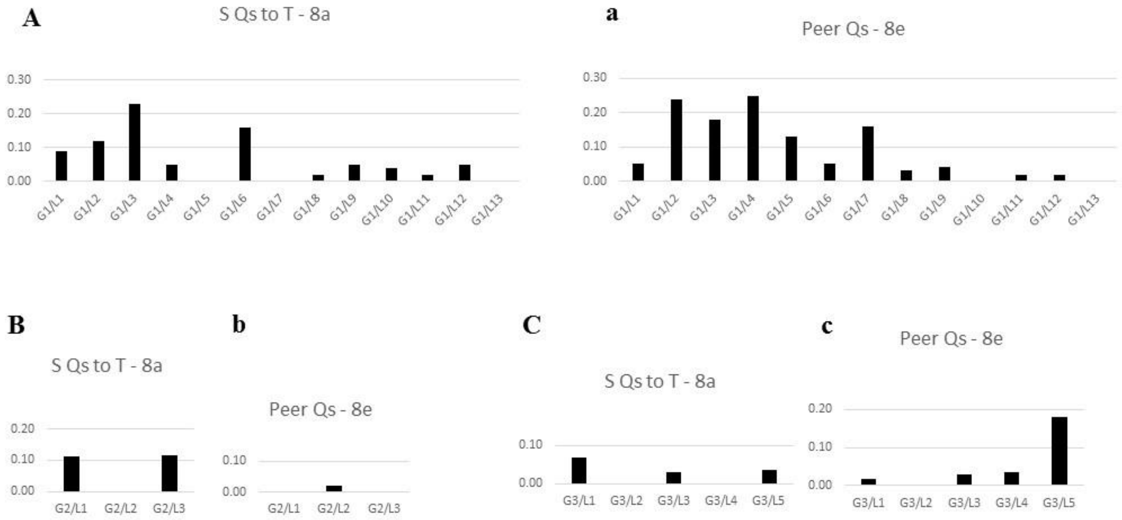


Figure 14: Weighted frequencies of student-generated questions for all groups

There were two approaches to encourage student-generated questions: to structure lessons that encouraged peer questions – i.e. Lesson 4 with Group 1 and Lessons 3, 4, and 5 with Group 3 – and simultaneously to encourage student questions to the teacher. Working with Group 1, the teacher paid a lot of attention and care to creating circumstances that would generate peer questions (Graph 14a). Hannah was intrigued to encourage her students to ask questions, but she had little experience how to achieve that. Obviously, the teacher was interested in evolving the lesson practices in ways that would benefit student interactions. Using practices she had used before, she modified her input to guide her students to more independent peer interactions during those activities.

Quote 15 – Interview from Lesson 1

> Researcher: I think the next would be, if that is possible, to make students listen to students. They do listen to you, they are very responsive to you […]. So if we can start getting them to ask questions to their fellow students or when they present their atom –

> mmm that's going to be in the next lessons – when they present their atoms, could you ask them to have questions from their peers?
>
> Hannah: They are going to do that in a slightly different way. It will be like speed dating where 10 of them sit down and ten of them will kind of rotate and sit opposite each other and say 'tell me about yours and I will tell you about mine'. So they can be questioning each other about particular ones [elements]. And that way they will be able to fill in their information. And they are always doing something, whereas – *I did it that way, thinking about what you said about getting them to question each other*. That's challenging. (my italics)

During the research and presentation of the historical overview of atomic theories, the teacher divided the group into eight teams, each of which had to do in-class research to find and present the most important breakthroughs of each theory. Students spent most of Lesson 3 reading books and gathering information from the internet, which they completed after school at home. In Lesson 4, each team presented their findings to their classmates. Lesson 4 was a turning point in the study with Group 1. Hannah introduced the structure of the lesson providing specific guidance about questions:

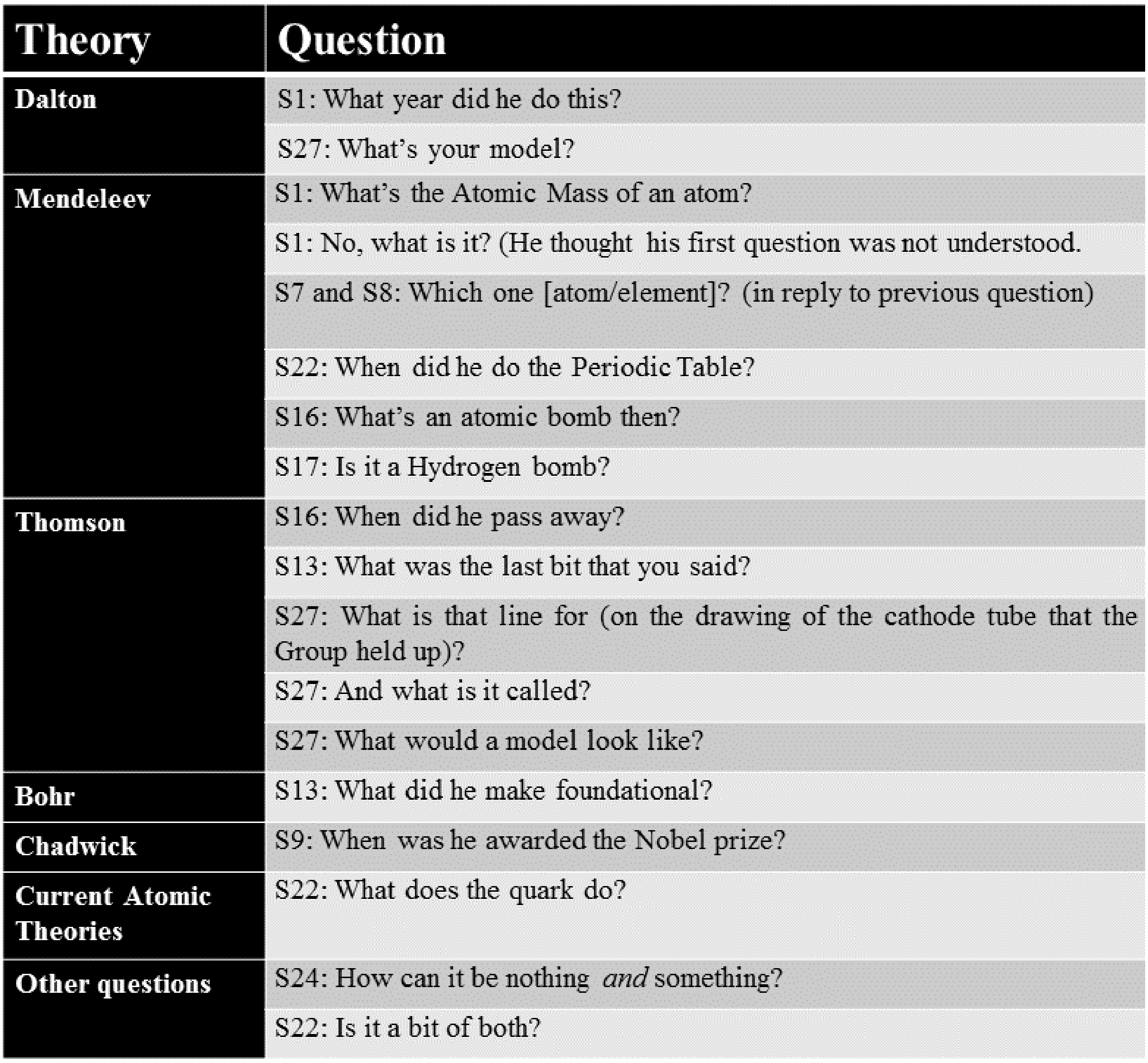
Quote 16 – Lesson 4

> Hannah: Well done, guys. Some of you have come up with some pretty cool stuff, some lovely presentations, some nice and colourful artwork. So now we are going to present our information and this is chronological. So what do I mean by that?
>
> S1: In order, time order.
>
> Hannah: In time order. These ideas, what I would like you to do, you all have your exercise books. Because you've only researched one particular era of this evolution of atomic theory, you need to be writing down notes that cover as many points as possible in your exercise books. So we've got [on the board], you're going to identify WHEN this was happening. Actually, you can do WHEN and WHO. You're going to write down ideas of WHAT the idea of the atom was, what is this thing the atom at that particular time. We've got to explain how they came to this model, what explanations, what experiments did they use which to give them this idea. And then we can use, we can apply our knowledge to previous ideas. […] While you are listening I want you to think of questions that you want to ask the guys presenting. Let's be a good audience, let's be listening, let's be thinking.

During the lesson, there were 17 student-generated questions to the presenters, all of which received a response. The table below includes the student questions for Lesson 4 (Table 20). In essence, the lesson design tasked the students with a double responsibility: (i) to present information that they had gathered from sources other than the textbook in front of the class, and (ii) ask questions and collect information for theorists they had not studied. To conduce the appropriate narrative, Hannah smoothly engaged presenters and audience to a Q&A session and encouraged students to interact with one another, further reducing her interactions with the presenters and leaving her questions last. From Table 20, the majority of questions are both shallow and relating to the narrative, i.e. ‘what year did he do this’, ‘when did he pass away’, and so on. There are questions of description, i.e. ‘what is that line for (on the drawing of the cathode tube)’. Finally, there are those questions that could be part of a debate, if the students felt the confidence of expertise, i.e. ‘what would a model look like’, ‘what does a quark do’, ‘how can it be nothing and something’. These questions required additional information to what was provided, further knowledge, possibly reflection and definitely grounded understanding of the subject. Admittedly, the students did not have those qualities to provide the necessary extra information to the questions, however, these were the first recorded instances that showed the student potential to generate thought-provoking questions showing CT ability.

This along with the w-questions for each scientist meant to compel students to pursue a journey of discovery about atomic theorists and to critically evaluate information. This group effort was different to the traditional individual process that Dewey (1933) and Ennis (1990) described as the journey of discovery and reflection. With Group 1, the individual process for CT development turned into a team process, to minimise pressure due to inexperience. This also agreed with the dialogical practices proposed in the literature (Chapter 3).

Table 20: Student questions, Group 1, Lesson 4



Theory	Question
Dalton	S1: What year did he do this?
	S27: What's your model?
Mendeleev	S1: What's the Atomic Mass of an atom?
	S1: No, what is it? (He thought his first question was not understood.
	S7 and S8: Which one [atom/element]? (in reply to previous question)
	S22: When did he do the Periodic Table?
	S16: What's an atomic bomb then?
	S17: Is it a Hydrogen bomb?
Thomson	S16: When did he pass away?
	S13: What was the last bit that you said?
	S27: What is that line for (on the drawing of the cathode tube that the Group held up)?
	S27: And what is it called?
	S27: What would a model look like?
Bohr	S13: What did he make foundational?
Chadwick	S9: When was he awarded the Nobel prize?
Current Atomic Theories	S22: What does the quark do?
Other questions	S24: How can it be nothing *and* something?
	S22: Is it a bit of both?

According to the weighted data in Graphs 14A and 14a, there were several lessons with peer questions at a relatively high frequency. From Graph 14A it is obvious that student questions to the teacher were high in frequency in the first few lesson but the frequency lessened as the study progressed. The qualitative data additionally showed that questions to the teacher had a more inquisitive character in the progress of the study. The students asked questions roughly but not closely related to the lesson content, looked for information that the textbook and immediately accessible sources could not provide. The questions in the quotes below aim to show the shift from merely looking for a textbook explanation to exploring further phenomena and asking about what they did not already know. This was taken as an indicator that student confidence in understanding chemistry gradually grew, so their questions expanded to new phenomena mostly sourced out of news stories or random references that unexpectedly seemed relevant within the chemistry lessons.

Quote 17

Lesson 2

S9: Argo is a noble gas.
Hannah: Can we ask a question about that?
S27: What do you mean? Like why it is a noble gas?

Lesson 4

Hannah: So we've got this atom there, that previous guys observed that this atom is a solid thing but actually now, Thomson comes along and says that there are bits within there that are doing different things and he found that the electron – he found out that there is electrons. We'll find out more about the electron soon.
S27: *What would a model look like*?
Hannah: A model? So if you were to draw an atom what would you draw it like? (my italics)

The first question required an explanation easily attainable as textbooks describe noble gas properties. This was quite early in the study. The second question reflected the student's effort to keep track of the development of atomic models from the presentations of his peers. A similar question had already been asked by the Obs earlier. In this case the student repeated the question – it was not the student's original thought – however, the CT contributor here would be that S27 was able to recognise a meaningful question and in repeating it S27 attempted to consolidate the information his peers were sharing.

Lesson 6

Hannah: Hydrogen and Helium, how they make a link together.
S5: How does it [helium/hydrogen] come from stars? How do we get that?
Hannah makes a hand-gesture showing an explosion and then asks the class: What do we think?
… (later in the same lesson)
S17: *What is a Hydrogen bomb*?

Lesson 10

S2: *How are the electrons formed*?
Hannah: How are the electrons formed?

S1: *Like what order are they in the shells*?
[…]
Hannah: Use the magnets to model what happens. What happens in the atom?
S27: *What are we testing*?
Hannah: As you go down the group, why is it becoming more reactive?

S5 asked about Helium and Hydrogen in Lesson 6 looking for an elaborate explanation of how stars in the sky are the source of elements on the earth according to the teacher's information. The question was seen as a CT indicator, because it showed that, on one hand, the teacher was guiding her students to learn chemistry outside the traditional sources. On the other, the response of the students to this practice was positive: S5 tried to conceptualise what she knew about the stars, what she knew about chemistry and create a link of how these two different entities connected together. Similarly, the question about the Hydrogen bomb followed a long discussion about the explosion of stars and the generation of elements. The parallels drawn by S27 between star explosion and the elements were interpreted as skill-building in drawing patterns for different phenomena and combining the little information from one source and putting it in the other. Though perhaps these patterns were not quite accurate, the ability to see patterns of chemistry outside the classroom, transfer chemical knowledge to references that came outside the class were attributed to the student developing their CT. In Lesson 10, the students were troubled about the decision of distributing electrons in the outer shells. Hannah had asked a relevant question about outer shell configuration in Lesson 5 without providing enough background information as an answer. According to the syllabus, this was advanced knowledge. However, by Lesson 10, the students had accumulated enough experience to now wonder about the rules that dictated the electron distribution in an incomplete outer shell. The last question 'what are we testing' was another indicator of change in students' attitude. Students gradually became accustomed to thinking about tasks independently, which reduced the number of questions they directed to the teacher. They discussed and collaborated with each other and they asked for help only when they could not work out a solution. Using their experience from previous tasks, their questions were more precise as were their actions. The request for further information was more accurate requiring the teacher to provide a more accurate input. The teacher expertise was seen as leverage to promote further study and in asking information from the teacher, the students were in charge of their learning asking for directions more than dispense of easily-accessible knowledge.

For Group 2, there was only one record made for peer questions, in Lesson 2, which was not caught at the audio recording. Questions to the teacher asked either for instructions or they were actually answers to teacher question but posed in an interrogative manner (Quote 18).

Quote 18 – Lesson 2

Samantha: So incomplete combustion is when there is not enough oxygen available thus it produces what? Does anyone know? It may be something that you have heard, something dark that comes when you have burnt things. Hands up if you know.

N6: *Is it like charcoal-y*?

T: Yes.

N6: *Like ash*?

T: Yes, you can call it ash. It's like a black residue

N6: *Is it like a black powder*?

T: Yes, you can call it that. And at the chimney when you have a black chimney. The colour is black/grey and called carbon monoxide. That's very important. So carbon monoxide is produced. So on your sheet it says "Incomplete combustion", under that can you write "not enough oxygen available, shoot and carbon monoxide produced".

N7: *Miss, how do I do it*? (my italics).

For Group 3, there were also few peer questions recorded in the observation data and in the video data the recorded questions concerned exclusively experimental process (Quote 19).

Quote 19 – Lesson 5

S312: Where are the test tube racks?

S313: We need to share them in the baths

S316 (from other team): Why is ours not working? Have we done it wrong?

S312 (while stirring the solution in the flask): How long have you – how long did your time run?

S313: Hey, aren't we supposed to use those [pointing at the catalyst]?

S312: No, not yet.

S312: S319, how long did yours take? Are we being tricked? It says 2-3 minutes.

S320: It took us 3 minutes.

S313: S323, how long did it take for yours to finish?

S323: 3 minutes.

S317: It's not going to change

S312: It's 4 minutes already.

S313: Hey, it's changed!

S312: It's 4.17.

S317 keeps stirring.

> S312: Should I keep on timing? It says I should stop timing when it turns colour, I stopped when it turned colour. Should I keep timing?
> S313: No. S317, you can stop stirring.

Procedural questions were shallow questions and the hope and expectation was for these to evolve to more meaningful questions, which was not observed. In Quote 19, it is obvious that students interacted closely within their teams, occasionally outside their teams as well, however, peer questions did not move much further than checking procedure. The progress observed by the last experimental lesson (Lesson 5), was that students were more likely to compare team results between attempts for consistency but also team results with other teams to verify that the process was correct. In Quote 19, the students' exchanges showed an effort to figure out why the experiment was not working, to find some reasoning for a failed experiment. However, during all experiments, the students seemed to be more focused – or distracted – by following procedure according to the instructions and less so in understanding what went on during the experiment. This is not to imply that following procedure was not important, rather to point out that merely focusing on that aspect of the experiment provided poor opportunities for CT interactions, i.e. discussing procedure, comparing results, negotiating an explanation. Asking questions to understand the microscopic aspect of the experiments, the importance of collisions, the accumulated data from the previous experiments, would have aided an explanation of what went wrong, when students did not obtain an expected result.

Another observation from peer questions in Quote 19 was that procedural questions often went unanswered. The teammates or students from other teams did not always bother to reply to questions from their peers. This happened frequently and it was attributed to the fact that all teams had access to the descriptive instructions and if necessary, each student could refer back to the instruction sheet. That was also true for experiments conducted in Group 1, which fed back to the observation that peer questions did not carry the gravity of a starting learning point, as the research assumed.

For Group 3, peer questions were mixed with teacher questions and exhorting, pointing to the relevant evidence that inferred the conclusion (Quote 20).

Quote 20 – Lesson 4

> Obs: S38, S39, and S310 can you please stand up and tell the rest of the class what happened to your experiment? And which one was yours.
> S39 stands up.

Obs: What happened to your group?

S39: S310 messed up.

Obs: What results did you get?

S319: Come on team leader! Can you just tell us what happened?

Obs: Ask more. Keep asking.

S319: What happened?

S38: It didn’t react.

S34: Why?

S38: I don’t know.

S319: What letter where you?

S38: 16, um, 16.

S318: Letter!

S38: Oh, H.

Obs: They told you nothing happened. And you have the tendency [concentration graph] of the reactions. What conclusion can you take from the fact their experiment had zero results. What was the unknown?

S39: Was it water?

Obs: Ta-dah!

The influence of the teaching practice in terms of questioning instead of lecturing was obvious in Group 1, where peer questions had favourable results within peer teaching (Quote 21). The way the students taught reflected Hannah’s teaching manner, essentially avoiding to give the answer and instead probing with further questions the correct answer.

Quote 21 – Lesson 8

Hannah asks S16 to help S10, S11 and S12 with the electron configuration. S16 goes to their desk.

S16: How many protons does this element have?

S10 and S12 Six.

S16: Six, right.

S11: How do you know that?

S16: The bottom one [Atomic Mass next to the symbol of the element in the Periodic Table] is six and 12 take away six, which is the amount of electrons. Then cover six [on the exercise sheet]. Do you understand?

S11: Yes.

S16: So you cover this one, then you cover this one [electron positions on 1st shell]. Then you cover this one and this one and this one and this one [electron positions on 2nd shell]. You can cover any other but I covered these ones because they are symmetrical.

S11: OK.

S16: That's all you do.

Overall, peer questions did not function as the successful critical thinking promoter that the research originally assumed they would be. When modelled positively, they were observed within a context as part of a discussion with momentum borrowed from other elements – explanations or discussions – and when the teachers were also involved in the interactions.

5.2.2.2 Student-generated explanations

In the codes under analysis, code 6 was used to signify students' answers to teacher questions, code 7 measured student answers to student questions and there was a separate code, code 8c (and 8c*), that was used for measuring the explanations the students provided. Arguably, explanations were frequently answers to questions. Alternatively, they came in the form of data/information presentations. However, code 6 was used for the occasions that students provided single-word or few-word answers or quoted a definition. Codes 8c and 8c*, on the other hand, were used for longer more thought-through utterances giving information and/or revealing the train of thought of the student to come to the explanation. These instances were often – but not always – noted in the Obs' reflective notes (Table 21).

Table 21: Observer's notes that refer to explanations provided by the students, Groups 1, 2, and 3

	Observer's note
G1/L1	Min 9: Code 8c: some conversation relative to the lesson. S provides an explanation for a process the T has asked them to do
G1/L1	Min 14: 8c* (with T encouragement - it was the first time code 8c* was used)
G1/L1	Min 36: S provided a full explanation of a process the T asked them to do voluntarily
G1/L3	Min 19: T asked S what his group intended to do and he provided an explanation
G1/L4	Min 34-35: Qs from Ss are really shallow "When did he die?" T tried to propel conversation. One S asked for the explanation of the cathode ray tube - how it worked
G1/L7	Min 36: Code 8c* - S explained to T individually at the desk why Chlorine and Copper are different
G1/L8	Min 39: Code 8c - S explaining to fellow S

G2/L1	Min 27: S’s explanation had critical elements – didn’t hear it very clearly though
G3/L4	Min 8: Ss start putting together an explanation of the experiments
G3/L4	Min 9: Ss participation in explanation
G3/L4	Min 28: Ss give an explanation (as to how the rate of reaction relates to concentration) and T elaborates on that
G3/L4	Min 57-58: Ss 34, 35 and 36 keep discussing the experiment, trying to work out the explanation to the change.

Explanations were distinguished according to whether the teacher prompted them (code 8c*) or not (code 8c), because progressively in the study, students were expected to readily provide explanations spontaneously, without encouragement from the teacher (Figures 15 and 16).

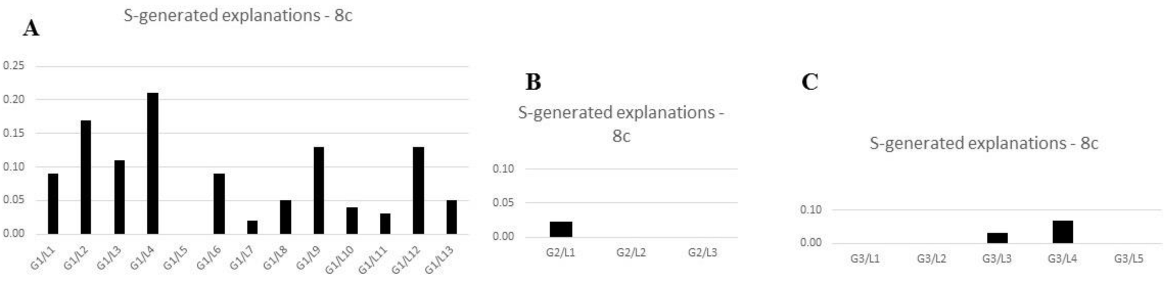


Figure 15: Weighted frequencies of student explanations for all groups

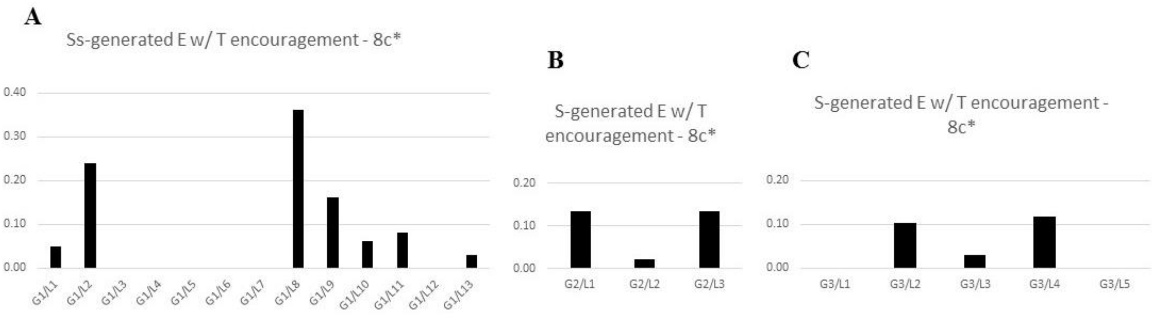


Figure 16: Weighted frequencies of student explanations with encouragement from the teacher for all groups

The observation from the analysis of data for the three groups was that at an initial stage the development of explanations relied largely on encouragement and reminding from the teacher. However, in Group 1, the greater length of the study and the adopted teacher practice of asking for explanations resulted in students growing in the habit of producing explanations spontaneously without being asked, perhaps at the anticipation of it. Though teacher encouragement always had positive results for explanations, once students came to expect that an explanation would be asked for, they often opted for providing it spontaneously. Groups 2 and 3 did not demonstrate the same tendencies regarding explanations and that was attributed to the teachers not prompting the students enough. From Figures 15A and 16A, the students overall did not seem to need less encouragement as the study progressed, however as Group 1 became more familiar with a new class practice they seemed readier to provide explanations both spontaneously and when encouraged (for example, quotes 24 and 25).

In the interviews, Hannah showed awareness and understanding of the significance of the explanation (Quote 22) and was able to conceptualise a way of helping students develop their explanation skills, which also required that she provided fewer explanations for them.

Quote 22 – Preliminary Interview 1

Researcher: So once they have formulated their [atomic] model, we pick up and ask them to explain it to everyone, not to you, to everyone. And if you then ask them “so what is there in between?” they should be able to observe and discover the empty space. Instead of you telling them, they will tell you.
Hannah: So draw it out through questioning? I like the idea about the wires.

Incorporating that goal to her practice, Hannah was instrumental in designing the chemistry lessons as pieces of a bigger picture, that being learning chemistry. This created a momentum for the students and each lesson was linked to all others, not necessarily in a linear manner. The aim was for students to become accustomed to reflecting on previous lessons to remember and collect the information that completed explanations at any given time in any lesson. Progressively, therefore, the students were building up a knowledge body they would utilise for providing explanations. This practice matched, in a way, McPeck’s concept of expertise, in the sense of helping students build some solid understanding about the atom and the atomic theory and expand those patterns of understanding to new observations and knowledge. To that effect, following the experiment of burning Mg in Lesson 1 (bright light, dangerous for the eyes, that dies after a few moments), a video was shown in Lesson 2 of a flare gun being fired. The flare burnt into a bright white light similar to that of the burning Mg strip. The expectation was for students to notice the similarities between the burning of the Mg strip and the flare going bright white and soon after losing all brightness and hypothesise a possible explanation regarding the ingredients possibly making up the flare. This practice aimed at providing an opportunity for generating a novel explanation, something that students had not read in their textbooks nor had they heard from their teacher before. Students were given a few minutes to discuss their observations to propel a peer Q&A. As the questions have already been analysed (previous section), in this section there is only the analysis of the answers specifically discerning shallow and deep explanations.

Quote 23 – Lesson 2

> S26: So S27, how do you think a flare gun works? As you can see there is a flare gun…going off [video on the screen]. So how do you think it works, S27?
> S27: It compresses (pause)
> S26: Can you give us a bit more detail?
> S27: So I think it uses elements, that is uh (pause)
> S26: So is that a scientific theory, S27?
> S27: Sorry?
> S26: Is this your scientific theory?
> S27: (laugher) it's a theory but it's an S17 theory [theory from another student]. So it's an element, it compresses an element, some sort of element that can create colour and still has a flare to it.
> S26: I agree.

Exchanges like Quote 23 were recorded frequently during the observations. Students showed some understanding of the content but could easily be stirred away from chemistry into the mechanics of a phenomenon, which was not sustainable without first establishing the building blocks of chemistry. In Quote 23, S27 did not make the connection of the observed bright light during the in-class experiment and the flare gun. The peer clarification questions in this example were cleverly vague but still provided opportunities for students to stick to short, descriptive, shallow explanations. There was an obvious difficulty in expressing themselves even among peers. This was attributed to lack of practice and lack of experience having to explain their observations. Additionally, in this instance and in other lessons early on in the study, students offered shallow explanations when unable to make the connections of information between lessons or draw on patterns of properties. Explanations to teacher questions were not of better quality. The students at the early stages of the study required considerable prompting to provide an explanation and even then the explanation was broken down in small parts:

Quote 24 – Lesson 2

Hannah: Could someone, please, articulate what did we see there? S4 you said second to…? Can you tell me what did you see there?
S4: I saw the Mg go to a white colour
Hannah: On the screen?
S4: It went bang-bang (laughter)
Hannah: So it went bang-bang. OK, S11, what was your conversation at your table and how is that linked to what we did the other day? **Line 5**
S11: So the Mg that went into a light when we put it over the fire
Hannah: So the Mg went into a light and …
S11: that was firing
Hannah: So that was firing [the video] and what we did, right. OK. What similarities have we got [with the Mg experiment]?
S7: It's caught light and um starts um kind of fire from um the gun fire set by gun powder
Hannah: Could be gun powder, we don't know what's in there.
S27: Gun powder is more explosive.
Hannah: So what happened then? What did we start with when we did our experiment? (Pause of uncertainty)
S21: Magnesium.
Hannah: We started with some Mg. And Mg is what? (pause of uncertainty)
Ss were quiet trying to guess what answer the T was looking for.
S21 (very quietly): A reactive element
Hannah: It's a-?
S21: A reactive element.
Hannah: A reactive element, lovely, nice word. So we've got an element and it's reacting.

Despite the teacher input and the explicit mention of the connection between the flare and the Mg strip, in the end, the students did not provide a full explanation or description of the connection of the two. It was safe to say they did not connect the two, they viewed them as two separate incidents. The partial explanations given ("I saw Mg go into a white colour," "Mg went into a light when we put it over fire," "A reactive element") were provided by different students with little obvious connection. S21 seemed to have some understanding of an underlying pattern of element behaviour when he mentioned the reactivity of Mg. However, even the teacher questions, which S21 answered, did not offer an opportunity to elaborate or attempt a full explanation. It was interesting how the many shallow questions often originated from one deep question: "what similarities have we got with the Mg experiment?" This question could propel both observation and recollection, a combination of an experience and its relating to other phenomena. In Quote 24, the students were not able to reach that level but introducing more practices focusing on similarities, differences, and observing patterns of properties helped students develop these CT skills.

There was a peak in teacher-prompted explanations in Lesson 8 (Figure 16) during which the teacher was recorded to ask several follow-up questions when asking students to develop their explanations. On other occasions, students provided explanations and background information about their thinking without further encouragement (Quote 25).

Quote 25 – Lesson 4

> Hannah: Guys, can you explain the experiments for me and the findings?
> S14: He [Rutherford] basically had this thin foil that was of gold and he had an α-particle beam which he pushed towards the foil. They thought it was going to go through, but it was reflecting on different directions, so he realised that something was different.

S14 provided an explanation of the information she and her team had gathered about Rutherford's contribution to forming the Atomic Theory mostly by repeating parts of the team presentation. Despite the repetition, the student had the ability to distinguish and collate the important information about Rutherford's work, which she included in the explanation. Furthermore, when asked for further clarification, S14 used her own language and not a rehearsed definition. It was a lengthy explanation with data collected from several sources and showed understanding of the information, an improvement in comparison with Quotes 23 and 24. Further progress, showed clearly in the following quote (Quote 26), where two relatively weak students were able to explain how they worked out an electron configuration.

Quote 26 – Lesson 8

> Teacher has asked student to draw the electron configuration of carbon.
> Hannah: Talk me through it.
> S17: There are six protons and there are six electrons.
> Hannah: Very good. And how have you arranged those electrons?
> S16: Six.
> Hannah: So there are six of them. How did you arrange them?
> S16: Two (pointing at the 1st shell) and two (2nd shell right) and two (2nd shell left) equals six.
> Hannah: And why did you put them in those spaces?
> S16: Basically, I put these two here because this is the first shelf and I put the other ones like this in the 2nd shelf to make them look equal.
> Hannah: Alright. You wanted to be symmetrical. Ok, nice, good work.

S17 and S16 had worked on the electron configuration of carbon together assisting one another in completing the task. S16 had better understanding how the Atomic and Molecular masses provided information for the number of electrons per element, and therefore explained the calculation process to S17 prior to explaining the process to the teacher. When the teacher prompted “talk me through it,” both S16 and S17 offered parts of explanation how they understood and actioned the distribution of electrons in the task. It took several clarification questions from the teacher to provide a more complete explanation of what they had done, but the students responded giving the thought process and an explanation of how they completed the task. They had no information of orbitals for placing electrons on a shell, but S16 had a justification for his choice of placing the electrons on shell L, which demonstrated that he had reflected on the matter somewhat. The teacher did not correct or guide any students about placing electrons on shells at any point. Group 1 utilised their knowledge and imagination to understand of how shells were filled and complete these tasks.

In line with the theoretical basis of developing critical thinking the students frequently demonstrated the ability to present information in a purposeful manner, make self-regulatory judgement and provide explanations when they got to the point of having to interpret their evidence (as quoted in the definition of critical thinking in section 2.1). Students did not mirror the teacher’s practice in explanations mostly because Hannah refrained from providing explanations. Instead, she prompted with more questions to guide students to reach understanding and verbalise explanations. Given that students were not equally confident in their chemistry skills, the positive impact of enabling them to input explanations stood proof that critical thinking as a classroom practice helped *all students improve their understanding of chemistry, regardless of their ability in science*.

Hannah also reflected on the success of this practice that enabled the development of the students’ explanation skills (Quote 27).

> **Quote 27 – Interview Lesson 7**
>
> Hannah: A critical thinking goal. You see a lot of the kids, (pause) one example. There were some kids who weren’t – who hadn’t got it and I could have gone through the rest of them (the content) but I thought it was quite nice that some of them did get it actually and then went on to explain it to other people.

In the teacher’s views, it was a success that some students were able to understand the content and boosting student explanations had the additional effect of improving student input and helping peers understand the content better. Student initiatives to offer or exchange explanations showed confidence, taking responsibility for their learning, and sharing own understanding with peers for reflection, correction, and occasionally self-correction. This was not peer teaching, rather an exercise for explanation and reflection.

Student explanations, similarly to questions were also infrequent occurrences during class visits with Group 2 (Figures 15B and 16B). The lack of more student explanations was attributed to the fact that the teacher covered most of the lesson time using a lecturing type of practice and repeating new information several times, thus providing few opportunities for student contributions. Even when she asked questions that needed either description of a process or an explanation, Samantha opted for providing these explanations first, thus answering her questions. Despite Samantha's preference to ask the questions in the lesson, during experiments or hands-on tasks, she did not ask her students to explain what they did and how, nor did the teacher prompts encourage students to share the thought process of giving an answer.

The students did attempt more explanations when the teacher encouraged it, however, the inference from observing Group 2 was that student initiative was not a favoured practice, unless when explicitly encouraged by the teacher. In Lesson 2, Samantha demonstrated two experiments, of which the first was a candle flame going off when deprived of oxygen. During that experiment, students attempted to offer simple explanations to Samantha's investigative questions (quote 28):

Quote 28 – Lesson 2

Samantha: Not heat. What's the fuel on a candle? (Pause.) What's the thing that you burn?
N6: The wax.
Samantha: The wax. That's the thing that you burn… and I'm going to light the candle (lights it). So I'm going to trap (with emphasis) the main product coming from it. This is called a gas jar, OK? So the wax and the Oxygen are reacting together due to flame with combustion and … what's happening, S11? What can we see happen?
N11: It's gone out.
Samantha: Why has it gone out do you think?
N6: Did it run out of Oxygen?
Samantha: Runs out of Oxygen, so the flame dies. So we go back to that triangle and I've got rid of the Oxygen and the fire has gone out. So I am lighting (pause while she lights the candle) that, so I can test the carbon dioxide. So this is called limewater. Does anyone know what colour limewater has?
N13: Blue
T: What was that? Did someone say blue? Yes, it is not blue, nice try. So it is…it goes cloudy. So what do I know has been produced when it goes cloudy?

N13: Carbon dioxide.
Samantha: Exactly. Very good, N13.

This experiment drove the teacher questions to become more inquisitive and less repetitive. She sought to encourage her students to visualise applications of the theory and explain the cause of the candle flame extinguishing. Though it was clear that the students did not feel confidence in providing answers – they answered with a question not with an assertion – still N6 was able to give an explanation linked to the theory she had heard earlier. Admittedly, these explanations were not profound, complicated, or sophisticated; however, they were evidence that the students were able to apply criteria to an action to give reasoning for it. This instance was encouraging evidence that when the teacher chose to use an investigative approach, the students were able to follow the progress from theory to practice and link the reasoning of a phenomenon to an occurrence. *Despite Samantha's scepticism on the practical applicability of critical thinking in teaching chemistry, her students showed potential for CT when the circumstances were encouraging.*

Group 3 also struggled with explanations. That was partly attributed to the lack of triggering questions from the teachers (as shown in section 5.2.1). Students had opportunities to provide explanations but they were unable to cross successfully the threshold of thinking about something and actually verbalising it. For instance, in the example below (Quote 29) the students of Team 1 felt confident that they had performed the concentration experiment correctly and yet they were unable to number some reasons why their experiment was not successful.

Quote 29 – Lesson 3

S32: Everyone's got results, everyone is done and they got two of them and we got nothing.
S33: We're doing it right, we *are* doing it right. It just doesn't want to work for us.
S31: Then we are pouring 20 of this. Wow, did you see how I got 20?
S33: Yeah.
S31: Ok and now we mix it and I go wash these things while these guys wait.
S33: Please, something happen man.
Mary: What solutions did you use?
S32: 18 cm3 –
Mary: OK, I just wanted to check. What did you use?
S32: This (pointing to the beaker with the letter K).

Mary: And it has not worked.

Students paused.

S33: We've done it right.

S31: They've done it three times right.

Mary: So what were you expecting to happen?

S31: We expected the X to disappear.

Mary: Right, it is not done right. OK you are going to have to pack up there because we are running out of time.

S33: It had to be ours, it had to be ours, you know.

S32: Why doesn't it work?

S317: Has it not worked?

S32: I know we've done it right.

Evidently, the normal outcome for Team 1 was successful experiments because they followed the steps in the descriptions of the experiments. When the experiment did not go as planned, the reaction was to repeat it to test the consistency of results, which was encouraged by both Mary and Harry. However, failure in the next attempts provided a critical thinking opportunity – as conceptualised in the research – for students to explain their process and with appropriate input from the teacher explore possible justification for the unexpected results. Though Mary asked students frequently whether they had followed the instructions sheet faithfully, the follow-up was "do it again" or "there is something wrong," which did not help towards reflection and critical evaluation of the circumstances and the suggestion of alternative factors owing to failure, for instance incorrect reactants. Another failing team, Team 3, were also unable to offer a full explanation but with prompting for the Obs the students were more confident when reporting no results for their attempted experiment. after two unsuccessful attempts they did not expect a successful one and stopped trying to make it work (Quote 30, my italics).

Quote 30 – Lesson 3

Observer: Exactly. Now what did everybody have when you went and collected your stuff? Everybody except your team, had something filled in here [picking up the beaker marked H]. The only difference with your experiment was that you didn't have this filled. You needed to fill it [picking up the capped bottle].

[…]

S38: *Everyone else had HCl acid in there but we didn't.* (line 4)

Observer: Exactly. That's the only difference.

S39 (to Observer): We need all of it?

S38: No, we only need 16 of it. 16, 16. 16cm3

[…]

Observer: OK, OK. Pay attention. Is something happening there?

S310: No. Bubbles only. Obviously we put something in there that caused the bubbles.

Observer: Are you timing this?

S39: Yes. There are tiny bubbles.

S310: *Bubbles are not supposed to be there, it is supposed to go cloudy. Where is that white dot?*

S38: It's working, it's working

S39: Can we shake it?

S38: No.

S310: How much time have we got? What 6 minutes? Let's start from the beginning.

[…]

Obs: I think it is important to know what a successful experiment looks like before you try again.

[…]

S310: It worked [another team's experiment].

Observer: How do you know it worked?

S310: Because they told me and I looked at it. It was cloudy.

Obs: Did you check?

S310: Yeah.

Observer: For yourself?

S310: Yeah. It is white and you can't see the X at all.

Observer: I see. This isn't happening with this one, is it?

S38: *Yes, because it is an unknown one, we don't know what it is*.

Obs: So (turns the instructions sheet around), take your times down here. So, you tried it the first time. How long did you record it the first time?

S310: 6 minutes, 33 seconds.

S38 (looking at the flask over X): It's not doing anything.

Obs: OK, so write down the time and the change that you saw or you didn't see.

S38 records times and observations.

S38 (to S39): What is the time?

S39: 2 minutes 30 seconds.

S38 writes the time and adds "no reaction"

[…]

S310: We're doing it one more time.

Team 3 had several challenges as a team, one being that the students did not collaborate until they were made to collaborate. However, they were sharp to observe that their experiment was not working. S310 was also aware of the transformation of matter that was expected. When S39 enthused over the formation of bubbles, S310 pointed out that this was not an outcome; it was probably an indicator that something was wrong. He was both observant and critical of what was happening in the experiment. When prompted, the team observed the experiments of other teams to collect solid data of the successful experiment. With further prompting and collaboration, the team concluded that the reason why their experiment was not successful was the unknown agent they were using. S38 specified ‘it is the unknown one, we don’t know what is in it’. The way the students handled the fact that their experiment was not successful showed method and maturity. It required external prompting and their explanation was not fully developed, however, within the timeframe for this experiment, they were able to record and report a result as well as offer a hypothesis for not achieving the expected result. They did not provide a sophisticated explanation, but it sufficed to explain the outcome. The projection from these observations was that had the study been longer and the request for explanations more frequent, the students would progressively volunteer explanations in a similar manner as observed in Group 1.

Harry’s teaching practices had a better effect on encouraging students to offer explanations. Harry prompted students’ thinking when questioning about reasons for observed outcomes. As shown in the quote below, he did not reject uneven or unexpected results, instead he asked the students to justify them, recalling perhaps prior knowledge.

Quote 31 – Lesson 4

> Harry: These are the results that you collected (showed an uneven concentration graph for the experiment in Lesson 3). So, put your hand up if you can tell me, anything any idea you may have as to why there is such a variety of results and maybe why they didn’t follow the trend that we were expecting. Only with your hands up. S318?
>
> S318: Because the substances that we put did not have the right amount?
>
> Harry: Possibly, yeah. It might have been that you diluted them wrong. That could be one factor. S323?
>
> S323: Is it the water? Just adding more water made a difference?
>
> Harry: Yes, the ones that were water and we tricked you with, sorry S32. We wanted to see if you could guess what was happening and what had gone wrong. So in that reaction there was never going to be any time that the thing changes colour. So we had this point (showing the lowest point on the graph) which took longer. So that’s another factor. What else? S35?
>
> S35: People stopped the timer at the wrong point because they thought they could not see the X.

> Harry: Very good. That could be the most important factor in this experiment completely. Because this changes so slowly, this colour change, people may have stopped it when they first saw the little bit of colour appearing or you may have stopped it exactly spot-on when it did disappear, or you may have spotted well after it had disappeared.
>
> […]
>
> Harry: Exactly. Very good. Some of you managed more than two repeats, which is excellent. So if you could go to change after three times, three close enough times give a very good average. Some of you had very different results and you didn't admit any um? What's the word I'm looking for?
>
> Students: Outliers.
>
> Harry: Outliers, very good. You didn't admit any outliers.

Asking students to recall reasons for skewed results, Harry effectively asked them to reflect on their own results and actions and think wherein the error lay for the concentration experiment. In Lesson 4, Mary and Harry both took some time to discuss the results of the experiment from Lesson 3, thus providing the space for reflection and motivating the thinking process (as also shown in Figures 15C and 16C). As a result, students did express hypotheses, which later led to an argument (analysed in the following section). *This opportunity to discuss results and experiments was not repeated again during Phase 1, and the lack of more opportunities for CT practices was largely attributed to that.*

Most of the data in this section has presented shallow or incomplete explanations, early attempts of students to verbalise their understanding of chemistry. The most significant data were generated with the cohort of Group 1 whom the teacher aided extensively and consistently in developing their explanations. Students in Group 1 ventured to give explanations even of phenomena that they did not have enough background knowledge or information about. In Group 3, the students attempted explanations for their experiments only when asked by the teachers in the short period of Phase 1, during the class observations. These explanations were the product of scaffolding information with questioning, which was not the normal class practice. Students were better able to provide snippets of well-thought, well-articulated information when Harry directed the class discussion. Group 2 did not present any significant data apart from the fact that students would produce explanations when the teacher asked for them.

5.2.2.3 The development of arguments

From the pilot study, arguments were viewed as the most challenging to attain of the three elements. Arguments, as defined in section 3.6, and as conceptualised from the pilot study, were follow-ups from explanations when the latter were contested. They were viewed as the culmination of prior steps: the question propelled the explanation, the explanation propelled further question mixed with doubt about the explanation, which in turn brought forward further supporting data to cement the original explanation. Alternatively, argumentation could result from direct disagreement with an original explanation, where students with opposing viewpoints presented new data that supported the opposing viewpoint. This environment for generating an argument was more likely to be founded on confidence in opinion from one or both participating sides in the argument. The key factors for the development of an argument are, in theory, doubt and ambiguity about an offered view or opposing viewpoints. Arguably, arguments require a level of confidence and students will argue only when they feel certain of their knowledge an understanding. Therefore, in the study, the expectation was for arguments to develop naturally from doubt or disagreement and there was no formal planning for fostering a debate in any of the groups. In the observation grid, arguments were not allocated a specific code, due to pre-decided practice that the occurrence of arguments would be noted in some details in the reflective notes. Therefore, none of the quantitative data reflected arguments.

Analysing the transcripts of Group 1, no actual arguments – exchanges in any form of debate – were recorded apart from few instances presented in the quotes below. There were few, sporadic moments that arguments started forming within Group 1 but did not quite develop to a coherent flow of exchanges where opposing opinions were tested and supporting data or evidence was provided – what would be defined as a fully-developed argument.

Quote 32 – Lesson 1

> Teacher has asked the students to use math blocks and model an atom. She now checks what the teams of students have come up with
> Hannah: So, S11, tell me why you have only one thing up there? What is an atom?

Hannah's first question ("why only one thing up there") was a challenge. Other students had multi-coloured representations and the teacher wanted them to compare and contrast their representations. However, Hannah had not established her later observed dialogical practice and this question did not spark debate. Similarly, S11 was not accustomed to contributing explanations or supporting her opinion so the opportunity was muted. Additionally, Hannah's second question led to a description-explanation, eliminating the chance for comparison of models and debate. Similarly, in the exchange below, though peers corrected each other in vocabulary they fundamentally agree in the information provided and there is no debate. The fact that they agree makes them assertive of the point they try to make. Establishing the assertion could then lead to an argument – not necessarily in the same lesson. The teacher input, on the other hand, prompted for more information, why-questions could be challenging but in effect, they were not. They all worked together towards completing an explanation, combining the knowledge and understanding that they each individually held.

Quote 33 – Lesson 2

S9: Argo is a noble gas.
Hannah: Can we ask a question about that?
S27: What do you mean? *Like why it is a noble gas*?
S2: I know what a noble gas is.
Hannah: Go ahead, tell us.
S2: It's this row here (showing on the PT)
S27: *Zero* (row zero)
S2: Zero.
Hannah picks up the PT from S2 and shows to class row Zero: Go on, S2.
S2: It's um (pause). They are all gases. They use them in lights and firework and things like that.
Hannah: *Why*?
S2: Because they are not that reactive.
S27: *Unreactive*.
Hannah: So they are unreactive. They are called (pause) someone said Noble Gases. Where does that word come from? Why Noble?
S24: Is it because they are steady?
Hannah: Steady. (my italics)

Quotes 34 and 35 were the only instances that came close to resembling an argument. In both instances, the students challenged in assertive manner something that the teacher said. In quote 34, S7 was able to oppose the teacher's view because his knowledge reached beyond the electron configuration of the first 20 elements. He knew there were more complicated configurations than the ones the class had practiced in and countered the teacher's view that the provided rule of thumb was a panacea for electron configuration practice (teacher assertion - "you can almost not go wrong with this" – student counter "in essence you could"). The response was an argument because of its tone of assertion, the countering of the teacher opinion, and the offer of additional evidence to support his opinion. The student had the knowledge and contradicted the teacher with the confidence of facts.

Quote 34 – Lesson 8

> Hannah: I made these white boards because see (circular representation of an atom and its shells)? How many electrons can be put in the first shell?
>
> Class: Two.
>
> Hannah: Two. How many electrons can we fit in the second shell?
>
> Class: Eight.
>
> Hannah: And third shell?
>
> Class: Eight.
>
> Hannah: Very good. You can almost not go wrong with this, though I have seen people go wrong with this.
>
> S7: In essence, you could [go wrong] because some them have over 18 [electrons].
>
> Hannah: Very good. This is only my basic level [of representation of the atom]. The better version would be printed in A3.

Quote 35 – Lesson 4

> Hannah: So what's most of the atom going to be then? If α-particle can go through it. You've got loads and loads gold atoms in there. So firing α- like that. So did most of them go through?
>
> S13: Most of them did, yeah. Some went back.
>
> S17: Some went back.
>
> Hannah: Some went back, so what did some of them hit then? If you're kicking a ball and you hit something, what's it gonna do?
>
> Class: Come back, bounce back.
>
> Hannah: If you are kicking a ball and it doesn't bounce back, what's it hit?
>
> Class: Nothing.
>
> Hannah: So what's most of the atom made of?
>
> S27: Nothing.
>
> Hannah: So we've got this idea of – Think about –
>
> S24: *Actually nothing is not nothing.*
>
> Hannah: S24, what?
>
> S24: *About what you're saying, atom is nothing. It is not nothing.*
>
> Hannah: Is it made of just nothing?
>
> S24: *How can it be nothing* ***and*** *something*?

Hannah: And so?
S14: *Mostly nothing*.
Hannah: Ah, thank you. So mostly nothing.
S24: *Mostly nothing, but there is something in there*.
Hannah: *Is it? I don't know.*
S22: *Is it a bit of both?*
Hannah: Oh my goodness, this is going to come a bit later. (my italics, bold in the original)

Quote 35 was rather more structured, though the student did not have assertive knowledge of content, having researched current atomic theories, she was aware that the atom had an entity and it also had the sub-particles: proton, electron and neutron. S24 stumbled on the teacher's use of the word nothing: the atom is not nothing if there are protons, electrons and neutrons, mostly nothing means there is something. In her question: 'how can it be nothing and something?' (emphasising the word 'and') she made the assertive statement that the atom had an entity. In the exchange, the teacher did not confirm that the atom was made up of something at any point. Instead, Hannah kept doubting that there was something within the atom, until the students came to the conclusion that the atom was mostly nothing. S24, joined by S22 and S14, argued about the entity of the atom drawing from instinct that the atom was an entity with sub-entities that were slowly discovered over time. Since the lesson was about discovery of the atom and sub-atomic particles these theories were the point of reference the students had, not experiential, purely theoretical. However, S24 did not have the chance to justify why she though the atom was not nothing.

Group 2 did not have the chance to engage in arguments during the class visits. The assertive steps that students in Group 1 experienced that on occasion led them to their assertive contradictions and argumentative exchanges were not observed in the few visits with Group 2. There was only one instance – quoted below – which was the result of an argumentative disposition rather than encouragement for an argument by the teacher or the willingness to offer a strong viewpoint by the student:

Quote 36 – Lesson 2

Samantha: […] OK, there is a triangle on the board and these are the three things that are needed to make a fire. What was the thing that we couldn't find? What was that word?
N2 (loud voice): Do you mean heat?
Samantha: Heat!

N2: I did say that!
Samantha: Did you say heat?
N2: Yes!
Samantha: Oh, sorry. We found everything then, fantastic. So, we've got oxygen, heat and fuel.

Though Quote 36 cannot be categorised as an argument, because it lacks content and it there is no disagreement, the instance was highlighted during the lesson because N2 was confident about the contribution she made and willing to challenge the teacher. Samantha's students showed potential to develop critical thinking during activities that created space for explanations, debates, questioning, although the teacher was sceptical about the value of developing CT in a such a young group of students and therefore did not opt to use any of the suggested teaching practices.

Arguments did occur more naturally in Group 3. As justified in section 3.5, arguing a position or an opinion required more in-depth understanding and knowledge about content, better construction of a response that would also be well-backed by further evidence. Group 3, surprisingly, was eager to debate different points of view. There were peer exchanges within teams that were a form of arguing (Quote 37), when students tried to convince each other about the proper experimental process. There were also the times that the teachers challenged students to compare results among teams, recognise patterns, and debate an interpretation of the results (Quote 38).

Quote 37 – Lesson 3

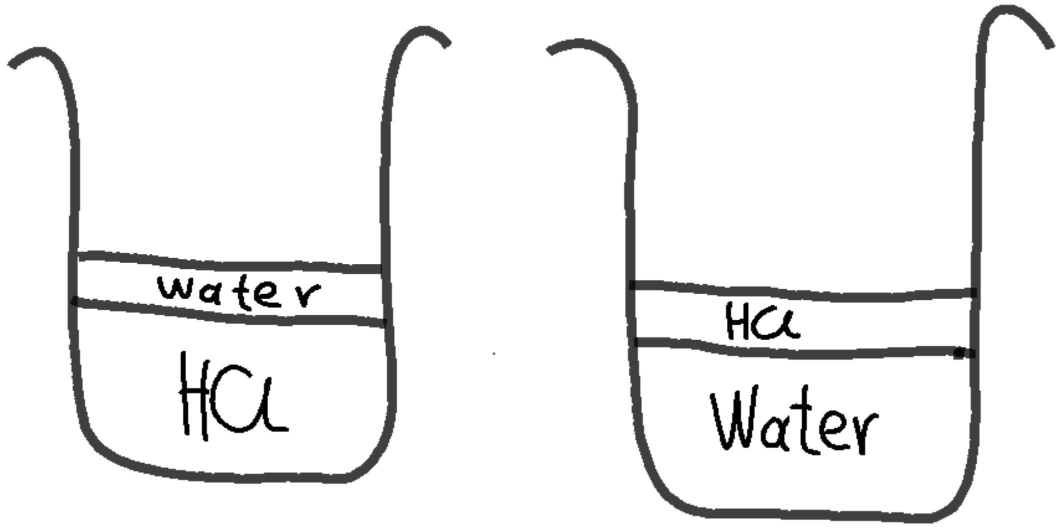
S38: Flask A contains this.
S310: So 20 of this in here (takes the flask that S38 is holding and pours it in the cylinder). How many is that? S39 tell me.
Observer: You should be the one checking the quantity.
All three are checking the volume in the cylinder.
S38: Stop.
S310 follows the instructions and pours until he has 20ml.
S310: There you go. Now you have 20 of this.
Harry comes around and tells them that they should be all doing the experiment at least one.
S39: So you pour it into this [conical flask].
S310 (reads the instructions): And then flask B - we need another flask, we don't have flask B.
S38: No this is flask B [where S310 just poured the solution].
S39: This is Sodium Thiosulfate

S38: No listen. Flask A contains 20ml – 20cm3 of 0.5 Sodium Thiosulfate, which is this. Flask B contains HCl acid which is this [shows the little capped bottle].
Observer: Alright, stop.
S39: Is that a beaker?
Observer: Guys, you need to decide.
S310: *You're not listening. Let me finish.* This [conical flask] is 0.5 of the Na2S2O3. We need another beaker for the HCl acid.
S38: OK, be my guest.
S39: Alright.
S310 fetches another beaker.

In Quote 37, the failing results caused irritation. After the first unsuccessful attempt, the team debated about the course of action they needed to take to complete the experiment. S310 asked in an emphatic tone that S39 should try to listen. S310 proposed a course of action to which S39 had certain objections. In reply, S310 read off the instruction sheet trying to convince S39 that there was value in the point he was making. S310 based the strength of his opinion solely on the instructions, however, his willingness to support his opinion made for a compelling arguing point. Notably, this incident occurred without any encouragement from the teachers and little interaction with the Observer. The disagreement regarding course of action in Team 3 built up the arguments within the team. From Quote 30 (p.174-5), S310 argued that the observed changes in the experiment (same instance as Quote 37) were not the desirable ones and the experimental process the team followed did not yield the desirable outcome, which meant the experiment failed (S39 "there are tiny bubbles" – S310 "bubbles are not supposed to be there, it is supposed to go cloudy").

Quote 38 – Lesson 4

Mary draws two beakers on the board and asks students how concentration affected the rate of reaction in the experiment of the previous lesson:



Mary: In which of these will the reaction be faster: the more diluted or the less diluted?

S319: *Is more concentrated.*

Mary: S319 please say that nice and loud.

S319: *The more concentrated the acid is the slower the rate of reaction occurs.*

Mary: Is that what we saw?

S36: *I think it's faster.*

Mary: Why do you think it is faster?

S36: We had 18 acid and it was the fastest rate of reaction.

Mary: *Ah! Evidence.*

S37: It was the longest.

...

Mary: Who did the one where – Who did the one, I think it was 14-6? 14 of acid and 6 of water? 16 to 4? What did you get?

S33: We got no results.

Mary: So yours didn't work at all? You got 16-4, OK? So 16-4, is that more concentrated or less concentrated than yours?

S37: More concentrated. Less concentrated!

Mary: Which one has more acid in it?

S37: Ours.

Mary: So is it more concentrated or less concentrated?

S36: More.

Mary: Right. We still have to come to a conclusion as a group. So you've got a minute more in your table. Say your conclusion.

S35: The more concentrated the faster it gets cloudy.

Mary: Why?

S36 (audible locally): My results told me that the less dilute the Sodium Thiosulfate the slower it takes to form a precipitate. (my italics)

At this point students started discussing their results and expressing their opinions. When the conversation continued:

> Mary: OK ladies and gentlemen. S35, S35, so you are on one side of the fence and S32 and S33 are on the other side of the fence. S35, what do you think?
> S35: I said that we had more acid and if we have more acid and the reaction picks up and is over faster.
> Mary: OK. S32, what did you say?
> S32: I said the more concentration of the solution the slower the reaction.
> Mary: So, is yours the same as hers or is it different? It's the opposite, isn't it? Hang on, S35, what are you saying?
> S32: He's saying "I still don't think that."
> Mary: S35, is that true?
> S35 (to S32): What are you saying?
> S323: He's going to change his mind now, watch.
> S32: I said, the more concentration the slower, the reaction. You said the more concentration the faster.
> S35: Yes, I still believe that.
> Mary: More concentrated faster? Ah, so we have two opposite points of view. Now have a look on the board.

Quote 38 was a debate that involved the whole class, required an overview of the data collected from all the teams, observation, recollection of process and knowledge. This was a successful both teaching and learning practice. On the one hand, the teacher put the debate in motion by asking for a theory regarding higher acid concentration speeding up or slowing down the reaction. Mary asked the students to share their thoughts and the reasoning behind their choice of correct theory. The students did have opposing viewpoints and therefore engaged in discussion and debate. S36 offered the first piece of evidence that supported his opinion ("ours was the fastest") which further fuelled the exchange of views and the teacher contributed to that by pointing out that evidence was important ("ah! Evidence") and scavenging more data from other teams. When the debate reached an impasse, the teacher asked for time measurements from teams with high and low concentrations, to put the debate back on the right track. These interactions between peers as well as the teacher input were viewed as most effective and conducive towards developing an argument and giving students the opportunity to think individually and collaboratively about explanations and the supportive evidence that made the exchanges more convincing. The ability of the students to argue was obvious in their compelling comments, their willingness to engage in conversation and use persuasion while conveying their point of view. This was the most fruitful instance for Group 3 where most students participated and offered opinions to both their peers and the teacher. The student contribution was longer and better structured than usual, which reflected both the way of thinking and the disposition of the participants in the argument.

Group 3 students' ability for critical comments and reflection of the lessons were also retrieved from the interview data from Phase 2 at the end of the school year (questions in Appendix 4). These comments related to the study by showcasing that students were able to evaluate both their contributions to the lessons as well as the circumstances surrounding those contributions. Students were able to share their views about chemistry as a subject, which most of them enjoyed and found interesting. On the other hand, they were also able to express both preference and criticism regarding the delivery of the lessons and views about opportunities for student contributions to be boosted further in terms of questions and explanations.

> **Quote 39 – Student Interviews/ Phase 2**
>
> S313 (Q2): I understand [chemistry] but if I don't understand something I go home and revise it. *I enjoy the lessons. Not while we had the trainee teachers*. I thought at times she was unprofessional. Not teaching us in a way. She concentrated mainly on people who understood it and it felt like if you didn't understand it you had to go home and revise alone. Whenever there is time, I revise alone. *I enjoy giving explanations, I find it more interactive.*
>
> S319 (Q4): Yes, definitely. *I like putting the things that we learn now into practice. I was teaching my cousins what we are doing. I was not only learning myself but I was also teaching them properly.*
>
> S316 (Q3): I ask the teacher. I ask the other students but they usually don't know, so I go to the teacher. *If my classmates give me an answer I think about it then I ask the teacher and if I get another answer I think about it.* (my italics)

The responses showed that the students clearly had a critical approach to the chemistry lessons, they had demands and expectations that were not always met. It was obvious that they were aware of the classmates that were good at chemistry as well as explained it well, so they admitted to often trust the peer opinions more. S213 argued about aspects of the learning experience he did not enjoy and offered explanations for his viewpoints. S319 explained how explaining chemistry to others helped her better understand it herself and S316 expressed the value of peer contribution to his experience. Responses from 20 students were gathered through this interviewing process and all of them were well-built and supported with evidence, explanations and justifications. When the students felt challenged with a follow-up question of why, they engaged in arguing their viewpoint. The questions were directly relevant to content, however students, in their responses, expanded to topics related to the class experience holistically. This showed that students had the capacity to be critical and could relate it to the classroom experience, but needed guidance to implement that in the lessons and relate it to the content.

In Group 2 – as the quotes above show – there were instances of doubt, or the occasional challenging question that could lead to the development of an argument, but none of the instances in the data featured an argument. This was attributed to the fact that students did not accumulate enough background knowledge in in-class activities to create a dynamic for an argument, which was the case with the argument examples for Groups 1 and 3. For the Year 9 groups, most often challenging questions were answered readily, usually without further challenge. The Year 10 group, however, took advantage of the challenging opportunities and participated in debating. The contrast between the younger debating group and Group 3 was that in Group 1, the questioners were observant enough to detect room for doubt, but not well-read enough to further explore the possibility of a different viewpoint. The confidence of expertise was built up slowly hence arguments developed in small scale. Group 3 participants however, felt more confident in their understanding of chemistry and did not shy away from talking out points of view.

The difficulty in developing arguments was stunted by several factors were required for arguments to occur. For the students those were confidence of opinion, concrete knowledge of all parties in an interaction, maturity of thought more likely to be present in older students (i.e. Group 3), genuine insightfulness and investment of time to gather further data. From the data in the study, teachers often diverted opportunities of argument to opportunities for explanation, i.e. Hannah. Hannah and Samantha did not often ask questions that propelled a debate. Hannah’s in-class activities served student collaboration but in most occasions, they did not require a contrast of opinion or information. The activities Samantha prepared for her students were individual and there was no room for debate. Also, Samantha revealed the solutions to the activities immediately after they were completed. As a result, argumentation did not have any significant impact on the development of critical thinking for the students. Analysing the examples of debate in Group 3 (Quotes 37 and 38), the experiments and the organisation of a debate as classroom practices engineered the promotion of arguments. As suggested, the debates observed in Group 3 developed naturally from disagreeing explanations and processes without an organised lesson plan springing from challenging questions or from challenging assertions.

5.2.3 The impact of teacher as an expert on student-teacher interactions

In the theory and the pilot study, lecturing as a teaching practice was viewed as a counter-effective means to the development of critical thinking. When students sit and listen they are more likely to be passive recipients of information and the non-active state makes the retention and grasp of content slower and more challenging. In the observation grid, code 4 was the description for teachers lecturing and code 5 was the description for instruction giving. In relation to critical thinking and the literature review in Chapter 3, lecturing was unlikely to help students cultivate their thinking skills within chemistry or develop deeper understanding of the content. In order to turn them to active listeners teachers would need to give them guidance for the content and space to let them reflect on what they did in action, what they were asked to do and the outcome of the action. The two practices – lecturing and instruction giving – were not coded together as instructions are by nature more technical and relate to hands-on tasks, especially common in chemistry. Instructions are descriptive but the students have to be engaged in thinking and understanding, if they want to complete the tasks.

Opting to use a teaching style relying more on code 4 and less on code 5 was also used as an indicator of teacher attitude towards critical thinking. The hypothesis was that teachers, who found value in CT as a learning outcome would opt to organise lessons that led students to completing tasks more independently, being more responsible for their learning and understanding of the content, hence frequency of code 5 would be higher. On the other hand, frequency of code 4 was closer to a paradigm of strict lesson structure wherein there was little time for student initiative. With this in mind, the research suggested that teachers lectured less, were less obvious experts in the study, in order to foster an environment for self-regulatory, criteriological considerations. Asking teachers to be ‘less experts’ implied avoidance to answer questions - especially when they suspected their students knew or could find the answers to – and instead of teaching content explicitly, they provided enough relevant, concrete information and building blocks for students to make inferences. Naturally, this entailed the risk of failing the lesson aims, which Samantha, for instance, questioned in the first interview:

Quote 40 – Preliminary Interview 1

Researcher: […] The goal is for teachers to take a step back and let students do more talking in the lesson.
Samantha: I see. But how? What would they say?

Three relating findings were observed in the data:

a) The more teachers engaged in practices that induced critical thinking (less obvious experts), the more positively students responded.
b) Providing space for independent task-completion and learning boosted students' confidence and therefore made them more active participants and contributors in the lessons.
c) Students showed criticality in other areas via comments or observations but unless the teachers encouraged it actively within chemistry, the skill did not transfer.

Regarding finding (a) from the list above, Hannah showed the most consistent engagement with the project throughout the study. She welcomed the feedback and her personal and professional moto was that there was always something new to learn. She did not feel that her expertise in biology lessened her ability as a chemistry teacher, but she did feel that she could still learn how to be a better science teacher overall. Her positive attitude about critical thinking linked to her own philosophical wanderings, which she could not separate from learning and teaching science. In the duration of the project, Hannah kept adjusting her teaching practices bringing her own suggestions on amending practices she already used as well as venturing to use practices completely new to her.

From roughly the second week onwards Hannah spent less time lecturing the students and allocated about half the lesson (20-30 minutes) to in-class collaborative activities (Figure 17). She provided her students with materials that they need to complete at their desks, assisting each other. During the activities, Hannah walked from desk to desk and talked with students about their progress. This often led to further questions of comprehension of the content, especially when the teacher thought a team found it particularly challenging to complete the task. Table 17 shows the observer notes describing Hannah walking around the class and asking questions (section 5.2.1).

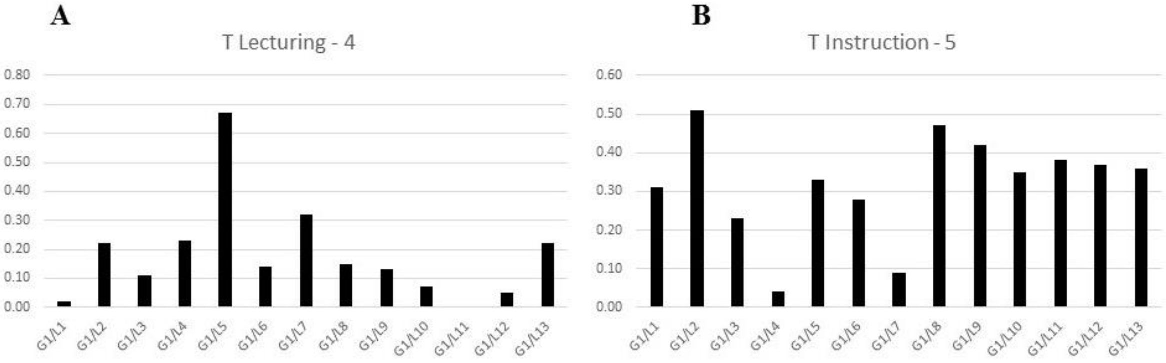


Figure 17: Weighted frequencies of teacher lecturing (4) and giving instructions (5), Group 1

Less lecturing reflected the way Hannah decided to be less authoritative in the way she presented new content. More instruction time – though not that much more from Figure 25B – agreed with the in-class tasks practice that Hannah implemented. Showing videos to present new theories also helped reduce the lecturing time, because the teacher was more conscious of the time spent passively watching a video, so she would break up the video-watching to shorter sections and pinpoint students' attention to specific information from the videos.

Note 2 – Lesson 6

Video resumes about the subatomic particles – protons, neutrons and electrons. Hannah says "Key" when hearing certain words from the video that she wants Ss to remember/retain such as protons and neutrons in the middle of the atom, nucleus.

For Group 1 the conceptualisation of Lesson 4 with the students presenting the various atomic theories was based on the idea that the teacher did not have to teacher from the place of expertise. The fact that Hannah was a biologist and not a chemist made her feel more comfortable with the idea that she did not have the same expertise in chemistry that she had in biology. Samantha and Harry, who were both chemists, were not able to do that. Lesson 4 marked a change in the classroom practice. It was the first lesson during the study that students occupied more speech time and the teacher had little control on what was presented. Hannah's stance modelled the non-obvious expert. She moderated the interactions and propelled students to prepare questions while they were listening to presentations (Hannah: While you are listening I want you to think of questions that you want to ask the guys presenting. Let's be a good audience, let's be listening, let's be thinking). After each presentation, Hannah invited questions from the audience before she asked her own questions.

During the interview that followed Lesson 4, Hannah felt that the efficacy of the lessons was at risk over the effectiveness of the study and that the uncertainty she felt was shared by her students. In her professional capacity, she was not convinced that the students had learnt what they would have learnt if she had taught the history of the Atomic theory in a lecturing format. Indeed, students did not retain a lot of the information from the presentations. As Hannah had not used the practice of student presentations to introduce new content, similarly the students had not been in the habit of expecting to 'teach' via presenting. This novel approach seemed to bear many risks, one of them being that the students left the class feeling equally uncertain about their learning due to the lack of the usual lesson structure. In reality, Lesson 4 created momentum for the teacher to share a vision with her students and motivate them to approach their learning with novelty:

Quote 41 – Lesson 5

> Hannah: So, if you had to describe what Thomson found out, if you had to explain how he found that out, if you had to apply what he found out in previous models. *Can you see how that is actually becoming more and more demanding?* And what we want you guys to do – because you are all aiming at these top grades – if you can develop as questioners and start to think beyond the concrete to levels further down and link these ideas yourselves, that is going to be really challenging for you, it's not comfortable. I said to Obs after our last lesson how uncomfortable I felt and how unsafe because I was out of control and Obs was smiling at me thinking 'Aha, that's exactly how we want you to feel, that's the point.' But I don't like it, because I like feeling safe and comfortable *and I like giving you questions that you can do and then we can do a crossword and then we can do a worksheet etc.* do you know what I mean? We like safety, it's human nature but does safety give us ideas?
>
> S7: Safety is boring!
>
> Hannah: Safety, necessary at times, but if we want to develop as scientists, as thinkers, as questioners we have to push ourselves a bit.
>
> S1: *How do we do it?*
>
> Hannah: We practise, like everything else in life. If something is new to us, we have to practise. That's why I said to Obs, I know I'll carry on with this. I've got to persevere.
>
> […]
>
> Hannah: I bet there were a few of you guys that left the lesson feeling frustrated because you didn't 'learn' anything in the 'oh, why didn't we get a worksheet with the questions that could answer that are concrete. Did anybody feel frustrated after that lesson?

Students: No
Hannah: No? […] The lesson title was ‘Evolution of – was it that? ‘Evolution of the Atom’?
Students: No. It was Evolution of the Atomic Theory.

Following this instance in Lesson 5, the teaching practice changed to in-class tasks for students to complete in small groups at higher frequency. Hannah had hand-outs prepared per lesson, electron configuration exercises that she asked the students to complete collaboratively and independently at their desks, small model-building projects that the students could try individually or in groups, or individually and then in groups. With these in-class activities, she promoted more student control over learning and offered opportunities for peer exchanges regarding the lesson content.

This approach to teaching practices reflected on the student frequency and mode of participation in Hannah’s class. It built their confidence in understanding chemistry, which, though not measurable, was evident in the ease students provided their views when collaborating over the tasks (note and quotes below).

Note 3 – Lesson 6

T avoids giving the definition, her approach is to ask for other words Ss with the prefix ‘sub’ to get them to discover the pattern and come to an understanding that ‘subatomic particles’ are the ones that are smaller than the atom.

Quote 42 – Lesson 12

[Students worked on Displacement Reactions]
Hannah: S3, make something up, please?
S3: Potassium fluoride and bromine.
Hannah: Ah! Very good. Can you answer this word equation, please? You have about two minutes. Potassium fluoride plus Bromine.
S1: Bromide I think.
Students (wondering): Is it Bromide or Bromine? Is it the same thing?
S14: Could be the same thing.
Hannah: The same thing as in would it react?
Studnets: No.
Hannah: Why?
S14: Because fluorine is already more reactive.
Hannah: Aha! So if fluorine is already more reactive, will there be a reaction?
S1: No.

Hannah: So we're going to have the same thing in the products: either Potassium fluoride and Bromine or we can simply write 'no reaction', yeah? Does that make sense? OK, let's make up one more. Let's make up one where there will be a reaction.

S16: I have one.

Hannah: Go for it.

S16: Bromine and um astatide.

Hannah: Astatide what? Sodium, Potassium?

S16: Yes, Sodium, Potassium.

Hannah: You have to choose one.

S16: Potassium astatide and Bromine.

Hannah: Try to solve that one, please. [Pause.] What are we going to make? Potassium astatide and Bromine.

Ss work on the equation.

S22: Does this exist?

Hannah: I don't know, ask S16, he came up with it. S15, do you want to tell us the products of this equation?

S15: Potassium bromide.

Quote 43 – Lesson 9

S7 (teaching the class): S2, listen. So on the first one – they are called shells, got two on the first one.

Hannah: Two of what, sorry?

S7: Can only have electrons. You draw electrons on these things. Get it (to S2)?

S2: Oh, wait a second. Is it two next to the electrons, is it two next to the nucleus, then four and then four again?

S1: No they're eight.

S7: Eight. Go in your Periodic Table and find how many electrons Lithium has.

S27: How do you find out how electrons we have, S7?

S7: What?

S27: How do you find out how electrons we have?

S7: You have to look at the atomic number.

Hannah: S2, what's the atomic number?

S2: Three.

Hannah: It is three. What is the atomic number?

S2: Three.

Hannah: It's the number of what?

S2: Protons.

Hannah: Very good. Take your Periodic Table out that will help you. So, S7.

S7: S2, if it can only have two electrons in the first shell where do I put them?

S2: On the next one.

S27: Anywhere [on the first shell].
S7: The three electrons?
S2: You put the three on the next shell.
S7: How many on the first shell?
S2: Two.
S7: How many on the next one?
S2 takes a long pause.
S27: It’s very easy.
S7: What’s three-take-away-two, S2?
S2: One.
S7: Well done (draws the three electrons on Li). Now basically, you have to write how many you have on each shell. So next to Li equals – how many on the first shell, S2?
S2: It’s one and two. One-comma-two. Isn’t it?
S7 nods negative. S7: It’s the other way around.
S2: It’s two-comma-one.
S7: Well done.
Hannah: Very nice, well done.

Hannah actively avoided answering the student questions, bouncing them back to the class and asking students to consult one another. This seemed to empower them to adopt the same practice in their peer communication relating to the lesson, i.e. S16’s contributions in lessons either generating a thought problem for the class to work on (Quote 42), or working together and explaining the rationale of his answer in a task to his fellow students (Quote 21). Hannah’s ability to be a less obvious expert developed the students’ ability to lead discussions and actively populate their learning with reflections upon their knowledge (Quote 43). Hannah’s practice guided the students to answer their questions and this seemed to motivate them to search for these answers with more vigour. With Group 1, the student response was positive in reflection to the positive attitude of the teacher.

Harry did not adopt as obvious an attitude as the non-expert as Hannah. He remained clearly the expert; however, his more subtle approach had to do with setting expectations regarding his students’ performance. He expected them to be able to answer his questions, he expected them to be able to follow the instructions and complete an experiment successfully. In these practices there was not change, except the suggested overall approach to design the same experiment for all teams but change reactants’ factor under investigation (concentration, surface area, temperature, and so on) per team. Mary, on the other hand, in her effort to follow the study guidelines struggled to organise her input in a manner that propelled the students to have challenging conversations. The struggle was mostly time-related. For Mary time-management focused more on finishing the experiments and less on holding reflective discussions about the data and observations from the data. The resulting influence on students was that the students focused better on procedure of experiment especially when the experiments failed and Mary persistently asked whether the instructions had been followed. To that extend the students did improve. However, there was not sufficient planning for those discussions that would get the students to verbalise and reflect on processes, compare data and start observing the patterns that would allow for theory-formation. This was obvious in the exchange of Teams 1 and 3 in Lesson 3 (Quotes 29 and 30), where the students were confident about following the process and could not find fault in their actions but where still unable to think of other factors due to which the experiment might have failed. The different input from Mary in comparison to that of the Obs reflected in the confidence Team 3 had in repeating a failed experiment and finding consistent data to Team 1.

In Phase 2 of the study for Group 3 the students were again engaged in experiments within coursework, which provided them with a lot of time to explore independently the factors they experimented on, recall the experience of the same experiments from Phase 1 and verbalise in more confidence their thoughts during their work. Though this was not recorded, the recorded conversations about their perception of chemistry and their performance in chemistry lessons included it critical comments about teacher practices, which they had not found helpful. The student answers to these open-end questions revealed that students had the ability to be critical but the skill did not automatically transfer in their chemistry learning.

Samantha did not adopt any changes in her teaching practice. As shown in quotes from Group 2, Samantha asked and answered her questions minimising student contributions and keeping the teacher in the centre of the learning process. She also took up most of the speaking time in the lesson, providing lengthy, repeated descriptions and explanations. Weighted frequencies for lecturing seemed to be in inverse proportion to those of instruction, though instructions were almost doubly as frequent as lecturing (Figure 18). Interestingly, Samantha's instruction-giving countered the assumption that more technical information could motivate students' CT skills, because of their technical nature.

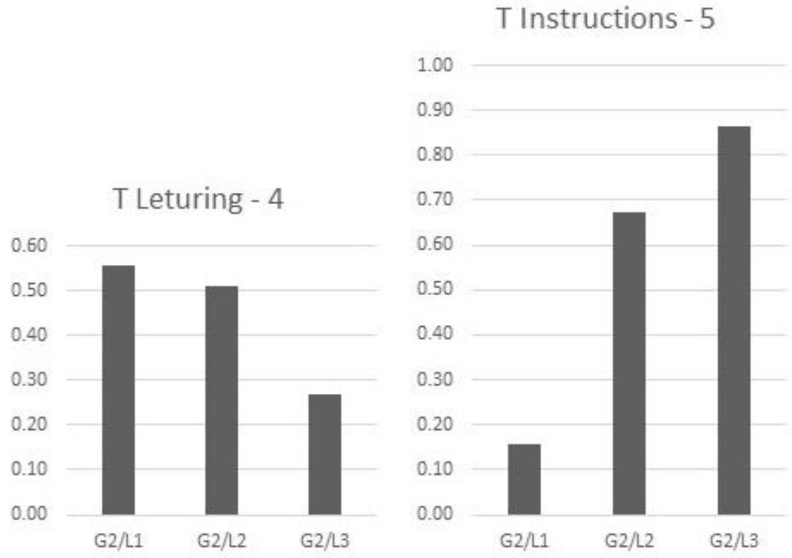


Figure 18: Weighted frequencies of teacher lecturing (4) and giving instructions (5), Group 2

Asking teachers to contribute fewer explanations and less lecturing in the lessons meant that students would have some newly founded freedom that they possibly would not know how to utilise to the benefit of their learning, as they were not used to this practice. This, however, was the point of the practice: to de-normalise students' ready accessibility to teachers' expertise and instead be guided to investigate chemical theory and phenomena for themselves. As shown, this recommendation met with different reactions from the teachers. Hannah accepted it as a practice but admitted that she found it inefficient a method of learning and that made her uncomfortable. She did adjust her practice to reflect that and her group provided plethora of instances where students challenged themselves, their peers and the teacher, all being indicators that they were using critical thinking more than before. Despite her hesitation, Hannah demonstrated the most successful practice with frequent reflection and support from the researcher. Samantha could understand the practice, but was not convinced of its validity; she, therefore, did not attempt it. The instances of criticality with her cohort were sparse – one or two – with no encouragement from the teacher and not necessarily related to the lesson. Harry and Mary each had a different approach to it. Harry did not deviate from his normal practice, which affirmed his expertise, but probed his students towards investigation at the same time. Mary misinterpreted the idea to mean that she was supposed to provide little information about the lesson content, which resulted to low number of questions, heavy focus on regulating experiments with sheets of instructions (as seen in previous sections). The data from Group 3 mirrored Harry's reserved approach as did Groups 1 and 2. Harry's students showed potential of criticality without reaching the peak of it, despite being the more mature group of the three with the ability to think and express themselves independently on other matters.

5.2.4 Lesson planning and success of practice per CT element

The participation of two Year 9 groups and teachers offered valuable opportunities for comparisons between different practices and how these impacted the learning practices of the students. Upon reflection of the teaching decisions of Hannah and Samantha, the latter was in favour of segmenting the syllabus in concrete units, whereas the former decided that chemistry was a whole and taught is as a continuum. In lesson planning where the lessons were part of a whole and there was continuity, students performed better in the in-class tasks and responded positively to practices for critical thinking. Hannah introduced each lesson by linking it to students' prior knowledge, experience, and learning. She organised the introductory lesson with an experiment that the students had done before. In the preliminary interviews about the project, the researcher view found a good fit with Hannah's practice (Quote 44):

Quote 44 – Preliminary Interview 2

> Researcher: Having a prior positive experience makes things a lot easier. So, let's talk a bit about the atomic structure. Lesson 1, you teach what?
> Hannah: I did it in two weeks.
> **[**…]
> Researcher: So about the history of the atomic theory [...] students already come with their ideas. […] We actually want to utilise whatever they come with […] instead of telling them [we ask] them to model what the atom is like […] explain it to everyone […] observe and discover. Instead of you telling them, they will tell you.

Hannah's practice to organise the lessons as a closely-knit continuum created a chain-like effect which in theory, should result in giving time to students to reflect – over a number of lessons – and help mature their understanding of the concepts. For instance, the research suggestion for the Atomic Theory was "split the content in two lessons one following the other," which Hannah developed even further. She started with a two-lesson organisation for the Atomic Theory (research and presentation, section 5.1) and went on to multiple-lesson organisation about the atomic and subatomic structure, which she linked to the patterns of the Periodic Table and followed up with reactions. The two-lesson organisation and layout created circumstances for the continuation of CT practices that empowered students to research, select and collate the information they included in their presentations and explanations, and learned enough material beyond the textbook to be able to reply to questions from the teacher and peers. Though there was high content retention from Lesson 3 to Lesson 4, as the students needed to know well what they were presenting, the overall content retention was low from Lesson 4 to Lesson 5. As Hannah suspected, the students did not seem to read their notes from presentations besides their own, which worried the teacher about the value of the practice. However, students demonstrated that the way they conceptualised the content did not necessarily fit the study's projected timeline, rather understanding consolidated at unexpected instances well after the study projections. For instance, in Lesson 10, the researcher and the teacher organised a concept exercise with magnets for students to study the change of electro-reactivity per Group of elements in the Periodic Table. The aim was for students to understand how distance and protection/attraction from the nucleus affected the electro-reactivity. Students were not able to get to any coherent conclusion by the end of the lesson despite the reflective questions both the teacher and the observer discussed with several groups. A month later, in Lesson 12, the magnet experiment re-appeared in reference as an attempt to explain electro-reactivity of Metals (Quote 45):

Quote 45 – Lesson 12

> Hannah: So, let's compile together an explanation, as we go down Group 1 what happens to reactivity and why. Who would like to start us off? As we go down Group 1-
>
> S1: The more reactive it gets. As we go down Group 1, the more reactive the elements get.
>
> Hannah: Excellent, that is correct.
>
> S7: Can I say why?
>
> Hannah: Go ahead.
>
> S7: Because as you go down – because the closer to the magnet they are together they are more likely to be pulled together, it's not going to be reactive much, because they are held together or something like that.

S7's explanation brought the reference that the teacher and researcher had hoped for in Lesson 10. The explanation, which S7 further elaborated on, was complete, coherent and correct and it informed the research that in theory the study meant to give time to students to develop their critical thinking skills, in practice the design was inaccurately driven by expectations for immediate results, whenever lessons were organised for them. This was a very powerful observation towards re-thinking the premise of the study to its original theoretical basis, that critical thinking outcomes take time.

Such occurrences were not recorded for Group 2, as Samantha's practice dealt with every lesson as a complete micro-module with specific aims to be achieved. Though Samantha relied on students' prior knowledge as well, the approach was more factual, i.e. she knew what the students were supposed to know and took that as a given base to build on (Quote 46).

Quote 46 – Interview before Lesson 1

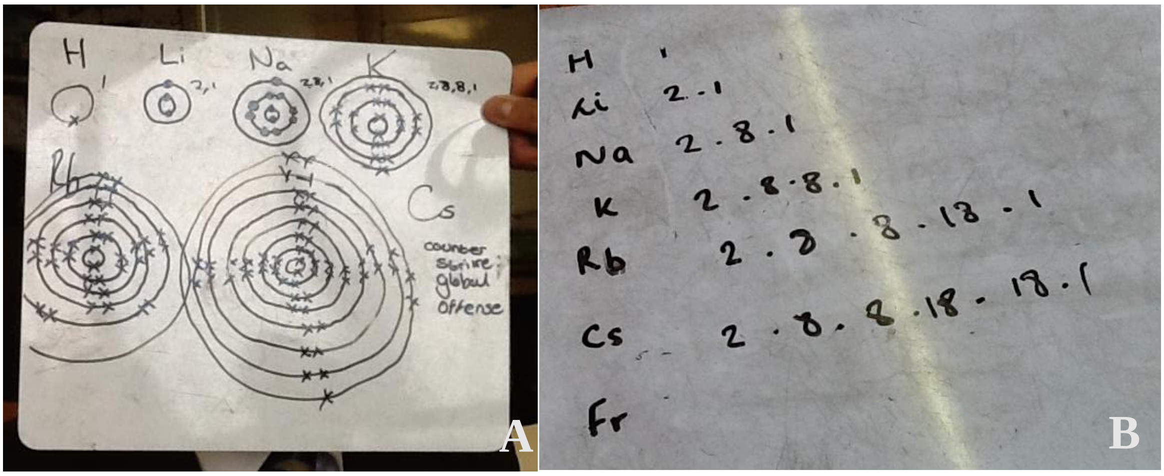
> Samantha: The Year 9 are doing a 6 to 8 weeks bridging period, which we've looked at the new specification and what they already need to know before the new course has started and whether they have already done it.

Group 3 also organised their lessons on a continuum per unit, which was equally conducive towards *gradually* building blocks of knowledge, reflection and understanding for the development of critical thinking skills, however, the fact that the Phase 1 was designed to last just two weeks did not foster similar occurrences. Further to that, since there was little time devoted to post-experiment reflection in Phase 1, it was less likely to observe such occurrences. Group 3, however, was an older and more mature cohort and their ability to collate information, reflect on it and tie it to an overall conclusion was demonstrated in their answers to the questionnaire. It was not related to the content of Collision Theory, but the fact that the skill was there fuelled the study view that teacher needed to sturdily guide students to develop and use these skills within the chemistry context.

5.2.5 The Impact of a Task-based Teaching Practice

As mentioned in Chapters 3 and 4, scientific inquiry as a practice encompasses many critical thinking skills. Experiments and hands-on tasks are common features incorporated into teaching practice, syllabus and curriculum with the purpose of enriching students' understanding of chemistry and microscopic interactions by giving them a first-hand experience of macroscopic change of materials. On the other hand, from the pilot observations and other teaching activities, it became clear that hands-on tasks that are not combined with reflection on the planning and thought processes are unlikely to promote the development of critical thinking or deepen understanding of phenomena. The three participating groups in this study invested time – more or less so – to hands-on experiences. With reference to Group 1, for instance, there was a notable shift in Hannah's practice favouring in-class tasks that required students to engage in thought-provoking, investigative exercises. Lecturing gave way to in-class task-based team activities that encouraged students to work with one another more frequently. That was a positive change as it created an environment of controlled independence within which students had the chance to remember and review the chemistry content they had learned, but also explore the depth of their understanding when the teacher added an extension to the task.

For instance, when learning about electron configuration, the class had thorough practise with the elements of Atomic Mass up to 20. However, when patterns of Groups 1 and 7 were established, Hannah asked her students to try out the electron configuration for Rubidium (A_{Rb}: 37) and Caesium (A_{Cs}: 55). The students had the experience of filling up to 8 electrons till the fourth period but filling the fifth and sixth shells required some mathematics and creativity to figure out correctly how many electrons would be placed in each shell. There had been no discussion about orbitals and the pattern changes of maximum electrons per shell from Period 4 to Period 5, so students used the rules they had been accustomed to for the configuration of Rb and Cs (Pictures 2A and 2B).



Picture 4: Two attempts of electron configuration for Group 1 elements of the Periodic Table

In Picture 4A the students applied the logic that each shell can take up to eight electrons except the first one that can take only two, and that the last shell can have only one electron as the element belongs in Group 1. In their calculations they did not take into account that the Group 1 element following Potassium (four shells) should have five shells. Instead they drew six shells and 36 electrons in Rb in total. Similarly, Cs had eight shells and the outer shell had three electrons instead of one, in order for the number of electrons in total to reach the number of Atomic Mass for Cs. Understanding the pattern of electron configuration in this case overtook the logic that Periods grew by one shell at a time. Though this depiction was wrong, it was interesting that students were confident about their configuration and shared it with their peers until they were questioned to correction. Picture 4B was a numeric configuration of the electrons around the nucleus of Rb. This configuration was correct, though there were no obvious calculations on the sheet. Unlike Picture 4A, there is little conclusion to be drawn about the thought process of the students completing the configuration in Picture 4B. This example highlighted the fact that the in-class task activities required that students went beyond what they already knew more frequently and both the teacher and students felt confident in this practice. This was an important achievement, because mistakes like the one in Picture 4A could be the starting point of discussion and debate when compared to the configurations like Picture 4B. The opportunity did not appear in this occasion, however, the potential did. Hannah encouraged her students to discuss their configurations between groups, though there was no class discussion.

A successful example of reflecting on previous practice when completing a task is shown in the quote below (Quote 47):

Quote 47 – Lesson 12

Students are working on the electron configuration for H, Li, Na, K.
S21: For Hydrogen, um…Hydrogen is, um. There is one Potassium because Potassium’s electrons are equal because they both have the same amount, so in Hydrogen there is one.
S22: Potassium?
S21: Erm, proton. I haven’t used them, I don’t know –
Hannah: It’s been a while.
S21: Um, protons. So for any element the bottom number stands for same as protons and electrons. So for Hydrogen it’s one. There is one proton and one electron. In one shell, the first shell, there can only be two electrons. In Hydrogen, there is only one electron, so you only keep one in the first shell. But in Lithium there is three electrons, so you can only put two electrons on the first shell that’s why you add a second shell too. To add the

> second shell, we have three in total. You can only put two on the first shell and eight on the second shell and then carry on the same, you add more electrons at a time.
> Hannah: Nice, S21. Really good.
> Hannah walks away.
> S21: I was thinking of Potassium. I was thinking of different elements. I was thinking of elements instead of electrons."

Lesson 12 followed a three-week break of chemistry lessons. Time however did not have detrimental effect on students' competence for complete electron configurations. In this instance S21 presented his reasoning about the configuration of H and Li to lead to the reasoning of Na. the success of the practice was also the admission of S21 that he had reflected on his knowledge of other elements that he had configured before reaching to this point of having to recall what the correct configuration for Na was. Interestingly, he needed little encouragement to explain that to his peer and prompted volunteered his thinking process to help S22 understand and follow the logic of configuring Na.

Samantha also assigned tasks to the students during the lessons. The tasks mostly consisted of white laminated sheets that students were asked to write answers on from the questions the teacher asked, i.e.:

Quote 48 – Lesson 2

> Samantha: Forest fire: so the firemen, make a fire break. They cut down a line of trees to stop the fire from spreading. So this is the forest and here is the fire, so they cut down trees here to stop the fire. What are they getting rid of by doing that? Can you write it on your white boards, please? So we have the forest and the forest is a lot of trees, OK? And what firemen do, they have a fire here there is a lot of fire and then they cut down trees here. What are they getting rid of when they cut the trees?
> N6: Oxygen.
> Samantha: Could you write it on your white boards?
> […]
> Samantha: Those of you who wrote 'fuel' are correct.

These in-class tasks were not successful in changing the teaching or learning practice to be more CT-oriented, mostly due to the fact that the teacher asked and answered the same questions several times before giving students the task. In this case when the task was given, the only skill to be exercised by the students was memory. In comparison with Hannah, Samantha's tasks had no different character or purpose to what they were before the introduction of the study. They aimed to help students remember, rather than encouraged them to think about information and its application.

Group 3 had an extensive exposure to in-class tasks, being a study embedded in a purely experimental investigation. The choice of the experimental investigation meant to bring forth the differences in process and results and propel peer and teacher-student interactions regarding opposing opinions, thought prompting and reflection. These could further guide to a conclusion and establish understanding of the link between process and conclusion. Though the tasks were a strong element in the study for Group 3, the reflection opportunities were not as frequent. As mentioned, when those opportunities arose, the students responded very well, therefore the lack of more enlightening data was attributed to the lack of more such opportunities.

Ultimately, from the analysis of the sub-datasets per group, it appears that critical thinking opportunities were plentiful in the context of hands-on tasks, as long as the teachers took the time to elaborate on these instances. The hands-on tasks alone were not enough to push students to their full potential. The most impressive results stemmed from teachers making specific references and inviting reflection in following lessons and guiding students to review, reflect, rethink actions and re-organise both the thinking process and thoughts after casting a holistic eye on those actions and interactions in the lessons. The literature made it abundantly clear that the development of critical thinking is constant and rigorous work towards bettering skills of observation and analysis, in combination with more philosophical traits, like the love and pursuit of truth, fairness and others. The shortness of the study with Groups 2 and 3 had an impact on the results, which were few and most often showed potential. While data in Group 3 portrayed a complete or near complete cycle of interactions, where thoughts, ideas, questions, and suggestions were contributed by teachers and students, Group 2 did not match with similar instances. On the other hand, the longer study with Group 1 offered more opportunities for instances to be recorded and for the model to be applied.

Summary

This chapter aimed to present the data from the three participating Groups with the use of ethnography. Trends and patterns were investigated with and across groups in order to present the findings from the data. Each Group had a different approach to the study; therefore the results were extensively varied. The presentation of results quoted teacher and student participants and the quantifiable data came from the observation sheets. The mixed methods approach for the collection of data created added challenges to the analysis, as the numerical and qualitative data had to be triangulated in order to complete the presentation of the study with each group. The chosen method of analysis attempted to depict the natural environments of the classrooms and whether these infused harmoniously with the implemented practices. Due to the small number of participants, there were no generalisable observations. Instead, the data analysed focused on successful implementations and their impact on teacher and student attitudes as well as teaching and learning practices. The discussion follows in the next chapter and aims to consolidate the overall impressions and bring the study to the conclusive point of whether critical thinking can be practically applicable in a chemistry classroom.

6.0 DISCUSSION

Chapter Objective

Following the analysis of the data presented in Chapter 5, Chapter 6 discusses how the findings relate to the research questions posed in Chapter 3. This chapter is about lessons learned, whether the elements of the Q-E-A triad present a coherent connection to each other and to critical thinking after seeing different levels of success in two of the participating groups and lack of engagement in one of the groups according to the findings. It further looks into the visual representation of a model and how it withstands scrutiny when examining questions, explanations and arguments in the secondary chemistry classroom and whether it can extend its application to the other school sciences.

6.1 RQ post analysis and literature review

The research question quoted from Chapter 3 was:
How can critical thinking be organised and used by teachers in secondary chemistry education using questions, explanations and arguments?

This question was further explored with the sub-questions:

a) What is the relationship between questions, explanations and arguments that allows critical thinking to develop?

b) What are students' attitudes when using questions, explanations and arguments?

In Chapter 5, we analysed the data that we gathered from three different cohorts of Year 9 and Year 10 students and returning to the RQ and sub-RQs and overviewing the data, we find that Qs, Es and As framed the structure of scientific inquiry in the chemistry learning environment. Reflecting on the impressions of the pilot, in the discussion we see that just questions do not suffice in the development of student thinking. The shallow questions established the building blocks, i.e. every student in Group 1 was able to do an exercise of electron configuration by Lesson 9; progressing to the deep questions, however, brought about rough explanations at the beginning. Lengthier explanations followed when the students acquired enough experience in completing electron configuration exercises and moved to attempts to explain configurations for atoms they were unfamiliar with. By Lesson 11, they had learned that the Periodic table was a pattern, they had practiced several patterns and even the weaker students could see thatan exchange of electrons between atoms favoured elements that exhibited specific patterns, such as Group 1 and Group 7 elements. Investigation questions overarching every investigation and the application of dialogical classroom practices led to peer interactions and student-teacher interactions that motivated the production of explanations. Once assertion was established among students, argumentation could ensue.

Taking time to define the terms Q-E-A (section 3.6) gave the necessary edge to Qs, Es and As. *The study examined the way each component interplayed with the others while encouraging the occurrence of all of them in a dialogical process of teaching/learning chemistry with the aim of developing students' critical thinking. It also allowed for expression and exploration of mistaken views, and practice towards CT for making judgements with the eventuality of engaging students to take ownership for their chemistry education and the development of critical thinking*. Questions had to have clear aims embedded, aims that went beyond fact- and progress-checking (listed as shallow) and rather provoked investigation, thought and reflection. Asking questions that went beyond fact-checking encouraged student explanations and peer interactions. These student explanations had to be built up from short and vague to self-explanatory and evidence-based towards establishing assertion. Once assertion was established from explaining, students meant to engage in arguments, again evidence-based with additional supportive information in response to doubt or dispute.

The differentiated approach of questions, explanations and arguments in the context of CT theories (as seen in Chapter 3) was the combination of the three practices – traditionally used in science education – bringing together the inquiry, analysis, evaluation, criteriology, assessment and argument in a continuous flow of re-iterations for discovery of the chemical phenomena. From the results and data analysis, the proposed practice had pedagogical extensions in providing opportunities for students to sharpen their thinking towards more critical and acute judgments, observations of detailed processes, combination of theoretical and experimental information. From the chemistry education viewpoint, the three traditional practices combined successfully to complement each other and attribute collectively specific meaning, form and purpose of the content. Chemistry was not broken down to distinct units; rather it was a continuum of learning and knowledge. As a result, the thinking processes followed the same flow resembling a network, connecting information and practice that the students readily accessed in their quest to solve their own questions. The chosen collated practice of Qs, Es and As fostered the ideals for critical thinking (inquiry, analysis, evaluation, articulation of results, etc.) that were explored in Chapter 2 while upholding the best practice pedagogies reviewed in Chapter 3. The demanding outputs from investigative questions, self-contained explanations and well-informed arguments had a beneficial impact on student thought expression and participation.

These practices, untested ideals at the stage of design, consolidated once they were transferred in the classroom. A guideline to the teachers was to ask deep questions more frequently, to try to mine the answer from the students as much as possible, without asking too many questions at the same time. From the results from the different groups it was eventually obvious that teachers could ask too many questions – which was not a novel observation – but that there was the possibility for teachers to ask not enough questions – which was a novel observation. Teacher questions in the lessons were not always well planned, however, the investigative question (as defined in section 3.6) ought to be planned to sustain the learning process throughout the module, not just the lesson. Viewing the investigative question as the initial point, it ought to be clear what the aim of the discovery is so that teachers can guide the actions and interactions of their students to that investigation at any given time and students have an anchored aim for their learning. The absence of the investigative question voids the critical thinking component of the learning and the traditional practice of breaking down chemistry to units counters the holistic approach to learning that the Q-E-A combination aspired to. The most accurate claim regarding teacher questions would be that they were most effective when teachers formed them according to the learning outcomes, combined a purpose to main question and the follow-ups to that and provided time for students to work out the answer.

From the classroom practices and the analysis, student engagement in both physical activities (experiments and in-class tasks) as well as intellectual ones (discussions, exchange of ideas, collaboration to complete a task, investigation across teams) worked to the benefit of the design. The practical-theoretical exercises suited well the qualitative-quantitative nature of chemistry and also fitted critical thinking purposes, boosting the analytical, data-gathering skills (practical side) and the disposition qualities (reflection on the analysis, evaluation, results, and so on). As the practices cultivated students' thinking devices, the effect on the tasks and experiments was for students to seek deeper understanding of their actions with the material using peer and teacher interactions. In Group 3, this was not extensively observed in Phase 1, which was attributed to the shortness of the class visits, but was more obvious in Phase 2 when students had more time to investigate similar phenomena and showed more confidence in the process.

Besides Qs, Es and As, which were clearly defined and therefore easily recognisable, classroom realities were busy with student contributions that were not Qs, Es or As, but helped guide students through the Qs, Es, As. For instance, in the quoted excerpts from Chapter 5, students offered opinions when responding, they interjected comments, debated, compared results, repeated information, summarised and concluded, and so on. These types of interactions collectively supported the explanations in particular, prompted deep questions and were labelled reflection devices that led to asserting explanations. Reflective devices were the intermediate step of appreciating what is known, necessary for the production of responses that fulfilled the definition of explanations. The results from the three participating groups supported the view that implementing CT practices in the chemistry classroom was unlikely to bear fruit without the reflecting devices between question (or similar type of investigative prompt) and explanation. Two of the groups had positive responses to the suggested practices and the reflective devices boosted the student engagement, one group did not with the respective result.

Reflection devices propelled discussion further because they allowed for falsifiable commentary of different types and moved the discussion to deeper exploration and understanding. The fewer the student interactions or student-teacher interactions, as observed in Samantha’s group, for instance, the less the support from asking a deep question to arriving at an evidence-based explanation. On the other hand, a successful, meaningful, deep explanation was more likely to result after several iterations of questions, comments, opinions, etc. occasionally not even in the same lesson (i.e. Quote 43, Group 1). Similarly, in Quote 38, the comments, ideas, contradictions that students contributed to the debate moved students from the precarious stage of expressing opposing opinions to the point of expressing their opinions more assertively. Once they had reached that point of security in interpreting and understanding the data, they started debating, verbalising their understanding openly to one another as well as contributing to the overall classroom discussion. Younger students used similar devices: comments, clarification questions – which were very often used in the interactions of Group 1 students – prompting comments from peers who tried to help each other understand the content, i.e. Quote 43. In these instances, in which reflection devices were identified, a common occurrence was the questions as activators of the reflective device and helped students engage in the intermediate step. The activator was the lead to the falsifiable intermediate wherein students negotiated individual understandings to reach to an explanation collaboratively, via clarification questions, comments, opinions, ideas that propelled them to think beyond the surface establishing the route of connection between question and explanation.

In the conceptual framework there was an instinctive assumption (attributed to experience and the pilot observations) that arguments would naturally develop when students habitually started to verbalise their explanations. The perplexity remained about the missing link that made explanations a springboard for arguments. Reflecting on the analysis of the results, assertion was the connecting link between explanation and argument. Assertion was defined as the basis for the argument, doubting which triggers further investigation, explanation, reference to new data, and the overall investment of effort to not only prove but also persuade of the rightness of the established viewpoint. The student participants in the study did not engage in arguments unless they were sure of what they knew and understood. When they did not feel certain in their opinion they opted for discussions, comments, the falsifiable intermediate, whereas in the case of arguments their reference aimed to convince.

To that end, they used reflecting devices to those insulating the gap between question and explanation, to traverse from explanation to arguing an established opinion. Re-iterating an explanation, with more probing comments, investigative input from teachers or peers fuelled the arguments and made references to evidence more concise. The differentiating factor for the reflective devices connecting explanation to argument was that these comments were of unfalsifiable nature. Each iteration meant to establish the assertion more firmly both to the mind of the arguing party and their audience. In each iteration, be that investigation or accumulation of secondary data, reflection, evaluation of own and opposing opinion and juxtaposition of opinions to the benefit of the argument, the devices provided reasons for the assertion to become stronger. The same way comments and other random contributions were the falsifiable intermediate between questions (the activator) and explanations, post-explanation commentary was the unfalsifiable intermediate for arguments. The students showed more empowerment to judge facts and evidence in the post-assertion status.

The age and level of confidence of the group also played a significant role constructing the reflection devices. Year 10 students, for example, were better able to sustain the reflection devices with less input from the teachers, as long as there was some iterative teacher commentary at points of stalemate or for guiding towards the correct explanation without revealing it. The reactions of Group 3 to perplexities were also revealing, in the sense that reflective devices did not have a positive impact if the conversation caused more confusion to the students in the end. Though this conclusion was self-predicting, it was important to recognise the type of input that left students more perplexed in the end of a discussion than they were at the beginning of it, i.e. Quote 10, Group 3. Missing from this interaction was a follow-up, (similar to the one observed in Quote 43, Group 1) where the students were given a chance to revisit their prior discussion/argument and possibly come to a consensus. Practices that augmented the perplexity were shallow questions, repetition of procedural information, the unclear aim of data overviewing.

6.1.1 Practices fostering Qs, Es and As

The research question and sub-questions quoted from Chapter 3 were:
How can critical thinking be organised and used by teachers in secondary chemistry education using questions, explanations and arguments?

a) What is the relationship between questions, explanations and arguments that allows critical thinking to develop?
b) What are students' attitudes when using questions, explanations and arguments?

In the effort to organise the classroom practices in a way that improved students' critical thinking skills and disposition made them more analytical, more thoughtful, better able to verbalise their thought processes), the teacher participants and I kept an open dialogue (recorded in interviews) where we exchange ideas that fostered interactions in the classroom. The teachers implemented these ideas to the best of their abilities and we reflected on the impact the practices had after the lesson. These interviews of reflection of the practice offered a thematisation of types of practices that worked well, compelled students to both act and explain their actions in chemistry. Those were dialogical practices that allowed students to come to conclusions via trial and error, with interactions being reinforced when students formed small groups and worked collaboratively. There was a distinct difference between the younger and the older students. The younger students interacted better in their small groups and were more willing to exchange ideas and views within their group as well as across groups. The older students were confident they could fair well individually in practice, following instructions. However, their interactions increased when it came to discussion of their results. Thus, the dialogical practices created the space for students to act, evaluate, reflect and discuss the premises of their actions and their theories, practicing in fact critical thinking by repeatedly engaging in longer or smaller explanations, self-refuting, self-correcting, correcting of peers, sharing understanding and so on.

From the results of the three participating groups in the study, there were practices that showed greater success in developing Qs, Es, or As the characteristics of which should be highlighted. From the datasets per Group, Group 1 had the longest study and the most successful narrative in terms of development of student questioning, the development and production of explanations, though less so of arguments. This was a young group aged 12 to 13. The teacher, Hannah, was a very positive and motivated participant and put a lot of effort and reflection in her teaching practice and in developing learning practices that helped her students think more and more frequently. Tracing back from the quantitative depiction of the lessons, practices with more peer questions were the investigation and presentation of atomic theorists (Lessons 3 and 4), the investigation of models and patterns in the Periodic Table (Lesson 7) and the introduction of the atom and the elements (Lesson 2). In these lessons students had to complete a task in order to understand aspects of chemistry that are challenging but fundamental concrete blocks for understanding chemical phenomena.

Explanations worked well with Group 1 as well. The students consistently provided explanations throughout most lessons. The most successful of those were Lesson 2, Lesson 4, Lesson 9 and Lesson 12. Lesson 4 had the highest recording of explanations because the students presented the results from their investigation regarding the atomic theorists. The lesson was structured to prompt students to provide explanations. Lesson 9, however, was a spontaneous occurrence and therefore more valuable. The students asked the teacher to let them undertake explaining the content of previous lessons to their peers, which the teacher agreed to. Having set the rhythm of providing space for student participation, the whole class carried on contributing with explanations and other reflective interactions (peer encouragement and commentary) for the rest of the lesson. By Lesson 9, the classroom practice had shifted to more active student participation and the re-iterations of the material, teacher and student contributions had strengthened understanding to the level of being student-sustainable. Lesson 12 was a recapitulation of the content coming back from a two-week break. Working on tasks that they had become accustomed to, the students naturally fell back to having peer conversation while completing the in-class task and explaining to each other their thought process.

Arguments were more elusive with Group 1, which was contributed to the fact that the students were not as assertive about their understanding as the older participants were. On reflection, one reason arguments were harder to develop with Group 1 may have been due to the success of the collaborative learning practices implemented. Getting used to working on tasks together may have made the students unwilling to openly argue on points of disagreement. Had a debate been organised with Group 1, the participation may have been as successful as with the questions and explanations. As the learning practices improved the students' attitude towards chemistry, they prompted understanding and reflection upon the content. With reflection and interactions becoming habitual for the participants in Group 1, the projected benefit of developing arguments would in theory have pushed the students to start considering materials from a multi-faceted approach, be more critical of their knowledge and understanding and that of others.

With Group 3, the quantitative data were less descriptive, rather the qualitative data provided more opportunities to identify the classroom practices that engaged students in explanations, questions, and arguments. In terms of peer questions, these were overwhelmingly superficial, not really prompting an investigation. Teacher questions were often procedural as well. The practices that had positive outcomes engaging students in reflection data comparison and contrast were the reflective discussions when overviewing experimental procedures. In Phase 2 the students were much more independent in doing their experiments and from those observations as well as their replies to the short interviews they relied less on the teacher for answers and more on themselves and their peers. They planned the experimental processes, executed them and troubleshot in the occasion of failure. In Phase 1 when the experiments were more teacher directed the students sought the guidance of the teachers more often. The primarily experimental content for Year 10 required a steady input of the investigative question from the teachers, as well as a reminder for verbalising explanations. On the other hand, a simple contentious question 'Does higher concentration/temperature/surface increase or decrease the rate of reaction?' was enough to prompt the group to contribute to an argument.

Overall, the practices, which imbued critical thinking and simultaneously had a positive impact on understanding chemistry, encouraged reflection in both a collective and individual manner, with peer discussions and interactions providing more independence for bouncing ideas. The repetition of either experiments or tasks helped establish the concrete blocks of knowledge that the students re-visited upon understanding and reflecting on new phenomena.

The importance of the investigation questions was imminent both when it was present and when it was absent from the classroom practice and the results verified the importance of leading with an investigation question. Finally, much-cited but also needing to be established was the student participation in the lesson. As long as the teachers allowed room for the students to act, interact, make mistakes and try to fix them, it normalised the development of CT skills and improved chemistry understanding.

As seen in Quotes 38 and 43 the classroom practices were most impactful when all three elements were present. Revisiting images from the data, in Quote 38 (Section 5.2.2.3 – p. 184) upon Mary's prompting students engaged in both discussion of results and argumentation trying to find an explanation that fit the data from the experiment. Similarly, a little later in the same lesson when Harry took over questioning as to why the data from the teams did not fit the theoretical graph, the students easily offered several suggestions where erroneous data could have been recorded. The interactions went on until the conclusion was reached and it lasted about 20 minutes of the hourly lesson. The highlighted detail in this quote was that the interactions had a purpose: to find out whether higher concentration increase the rate of reaction. The investigative question ‘how concentration affects the rate of reaction’ became more concrete with reflection on the experiment: was it higher concentration that increased the rate of reaction or lower? The students revisited data of own and other experiments had to collate them and interpret what the numbers meant in terms of explanation of the rate of reaction.

Opening the discussion with the observation of more concentrated/less diluted versus less concentrated/more diluted solution, the teacher initiated the interactions using the drawing and an accompanying question. With questioning and prompting S319 was the first to present her conclusion ‘The more concentrated the acid is the slower the rate of reaction occur’. The teacher followed with a second question ‘Is that what we saw?’ prompting other students to share their conclusions from their observations, which led to S36 expressing an opposing view ‘We had 18 acid [the highest concentration] and it was the fastest rate of reaction’. Expressing the two opposing views as assertions drove the group to participate in the follow-up exchanges until a conclusion was reached. This image (Quote 38) holistically showed the progression from the investigative question to reaching two points of assertion, which naturally led to an argument.

Quote 43 from Group 1 was another prime example of mostly student-led lengthy interaction where students spontaneously implemented the three elements to the best of their ability and with impressive efficiency. This interaction had far fewer interjection from the teacher and the teacher comments and questions were strategically dispersed among the student interactions, when Hannah thought that more detailed information, descriptions, or input were necessary. Though S7 was mainly responsible for explaining the electron configuration, S27 aided in the process either with clarification questions, i.e. ‘How do you find out how electrons we have, S7?’ or with correction comments or offering encouragement (‘It’s very easy’). This image was successful because the students managed to engage in meaningful and meaning-making exchanges, which had positive results in every iteration. The repetition from the practice from student to student strengthened the concrete blocks of knowledge for electron configuration and asserted understanding and explanation. Simultaneously, the teacher modelled the role of consulting expert without imposing in the interactions, which enhanced the opportunity for reflective devices to flourish. There was no momentum for building argument, but it was a dialogical, student-led example.

6.2 Framework of CT based on the Q-E-A concept

This section specifically responds to the question:

What is the relationship between questions, explanations and arguments that allows critical thinking to develop?

The aim was to find whether Q-E-A was linear or teachers had to take into account more attributes to this combination of actions towards scientific inquiry in order to help develop students’ CT. From the teachers’ point of view, the progression was that they found best practices of utilising question, to draw out explanations, challenge students and encourage them to provide further data – almost in an argument-like manner, but often lacking the conviction. In the framework, banter among students in an effort to find an answer that was not considered fruitful, transformed to reflective devices, recognising that the students needed the space to recycle and accumulate their thoughts in the process of reaching a point of understanding and assertion. The teachers who provided saw better results in students’ understanding, participation, explanations, and the occasional argument, in comparison to the teacher that did not. From the student perspective, engaging in in-class dialogue was helpful for them to express their ideas, reiterate their thoughts, revisit the investigatory question and have some back and forth exchanges that cultivated better understanding and within the peer discussion led to better self-expression of own views.

In this section, I further discuss a framework that shows clearly how the Qs, Es, and As connect to enhance critical thinking in practicing chemistry education when including reflective (and self-reflective) spaces in chemistry education. The research questions aimed to investigate the relationship between Qs, Es and As, test if there was a coherent linkage and if the three elements had beneficial CT results when used in a combination. Initially, it was presupposed that all three co-existed in some form but did not necessarily co-develop. Explanations were linked to questions, though the former were not particularly favoured by students; arguments came up in the lessons but without underlying structure or purpose often without a plan. These occurrences lacked aim towards CT and therefore there was not consistent contribution towards developing CT. Observing the successful classroom practices, the original assumption failed to account for the reflection devices and their progressive nature. Additionally, the suggested practices in the study clearly meant to influence students' thinking habits to make them keener thinkers, more observant, more agile in investigating before making a judgement.

Reflecting on questions, explanations and arguments, how they were envisioned in theory and implemented in practice during the study, they emerged in the classroom practices gradually in the re-iterations of interactions, the encouragement to revisit materials, ideas, re-evaluate results. That brought together the purpose of having questions, explanations and arguments not co-exist but more importantly co-develop to create a sequence of exercises that focused thought on the investigative question and how it could be solved. When developed together as a process, the three elements fostered a nuanced conceptual framework for developing critical thinking. The framework resembled a loop that encompassed the re-iterations, connected the investigative question to the explanation and the argument not directly but with the interception of the reflective devices (Diagram 1). Each of the three pivotal points, Qs, Es, and As, demanded and expressed critical thinking and the development from one point to the next tasked the students with careful revisions, comparisons, and contrasts of their knowledge, understanding, verbalisations of thoughts, as manifested and analysed in the results. The initial point of the framework is set to be the investigative question, which with successful iterations helps students progress to structuring explanations of the phenomena in chemistry, moving along falsifiable intermediates. The purpose of the falsifiable intermediates is essentially to allow for the false explanations, comments, ideas, opinions, that once reflected upon are rejected and re-iterated to reviewing the investigation. Establishing the explanation encourages the students to argue for their opinion. At the point of argument, the investigation goes further than the immediate context to similar phenomena, which may be explained using the same logic. When an argument drives to the correct theory, it establishes knowledge and simultaneously asserts a successful thinking framework, thus building up CT. Using the CT momentum to get to that point of competence, the student can be critical not only of others but of themselves, they reflect habitually and are consistently rigorous in inquiry, investigation, analysis, evaluation, interpretation, criteria-setting, making judgements.

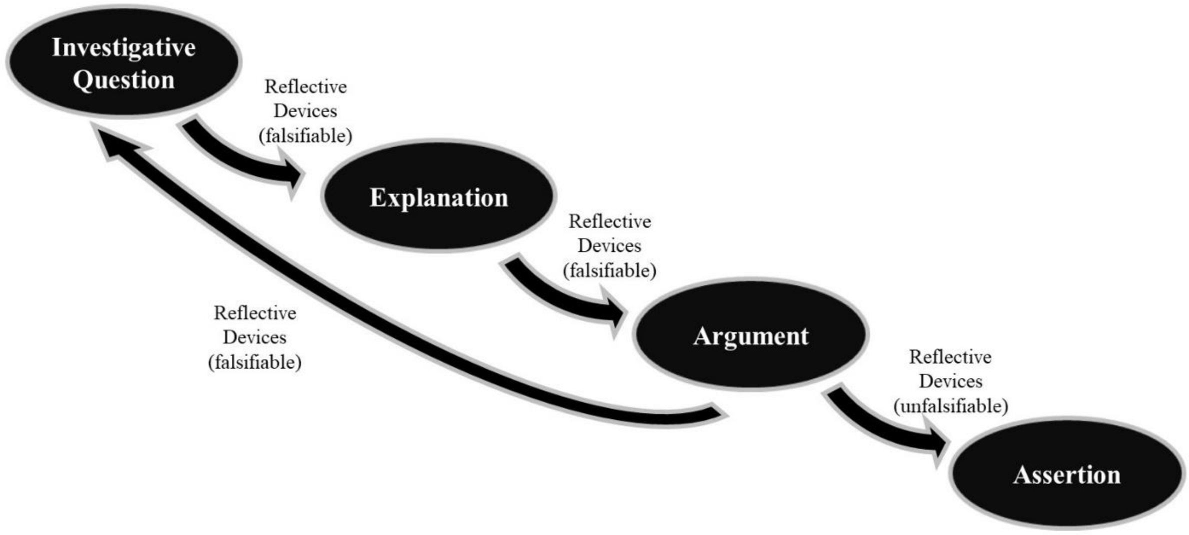


Diagram 1: Conceptual framework for critical thinking in chemistry education

The framework (Diagram 1) attempts to depict the way students interact with each other and the teachers when using Qs, Es and As to develop critical thinking. This also enhances their understanding of chemistry. The investigative question is the activator for thought and follow-up questions are part of the reflective devices. A question is – as shown in the data as well – most frequently the initiation point of a thinking exercise, however, there is a differentiation of the investigative question and the questions populating the intermediate spaces of the reflective devices. The investigative question signifies the initiation of the inquiry and remains the main focal point throughout the inquiry, the subsequently generated questions add to the motivation and re-iterations of thought while prompting the ability to think more critically. Both types of question are significant in the process.

Posing the investigative question did not lead the student participants to readily transition to producing explanations. Instead, in the dialogical context (section 6.4.1) they opted for collaborative and negotiating reflection devices. In the case of thinking exercises taking place after an experiment, revisiting the experimental processes was part of the reflective devices. Thinking exercises before an experiment were more abstract and modelling the content was organised by the teacher in in-class tasks. In every case, with encouragement from the teachers, the students engaged in interactions that scavenged their concrete blocks of knowledge, to reflect on them, re-think them, exchange, oppose or most often correct opinions and ideas about them, and finally re-evaluate and combine them to an explanation that seemed to logically account for a phenomenon. This process from the question to establishing an explanation organically allowed students to feel comfortable in expressing mistaken views hence described as the falsifiable intermediate.

Bridging the explanation to the argument required another intermediate of reflective devices. This reflective intermediate was more detailed as opinions and assertions were established and the peer/teacher interactions were more challenging in nature (i.e. Quotes 38 and 47). This intermediate space was unfalsifiable in nature for the prevailing judgement so moved the students further to constructing a judgement and a sounder thinking framework. For the disproven judgement, the reflective devices belonged to the falsifiable intermediate of trying to re-establish assertion by re-visiting the investigation. As the evidence in the argument supported the participants' theory or the experimental phenomena, the extended prospect of the framework projected that the students became more aware of their thoughts, opinions, and evidence from the content and their input in the lessons moved away from the shallow occurrences to deep ones. Questions were not just investigative but challenging, explanations included more minute detail. Though this was not extensively observed in the class visits with Year 9 and Year 10 students, there was enough development of the ability to express internalised thought process for students to be able to verbalise their explanations and participate in arguments. It is projected that once students establish their individual thinking processes, the framework above would see a more frequent turn-around of interchanges between explanations and arguments. For mature critical thinkers, the culminating point would be to ask their own investigative questions, thus depicting the ability to apply the arguing concepts to new phenomena, hypothesing explanations and engaging in an inquiry independently. That would require more exposure to CT practices, maturity and a better level of expertise in chemistry so it would reflect more accurately the efforts of older students.

6.3 Students' attitudes towards Qs, Es, As

Student attitudes were the focus of RQ (b):

> What are students' attitudes when using questions, explanations and arguments?

In the course of the study, it was obvious that student followed the rhythm of the teachers in the practices the teachers chose. The more the teachers allowed for discussion and analysis in small groups; the more the teachers encouraged comparison of evidence amongst groups; the more the teachers enriched the types of contributions the students made in the lessons, the more likely the students were to follow that practice. In that fashion, Group 1 had a very positive and energetic participation with peer questions, interactions, questioning the teacher explanations on occasion, taking on the responsibility of supporting fellow students in their learning. This fit in with Hannah's attitude to persevere in the study to investigate whether her students' critical thinking abilities would improve. Samantha, who opted out of trying out a practice different to the one she was accustomed to, had no results apart from few occasions her students mad a contribution that was attributed to the student disposition not the teacher encouragement. Harry and Mary who tried to incorporate refreshed practices of evidence discussion, keener observation autonomy for experimenting to a certain level, had mixed results, until Phase 2 when the students felt clearly more confident to perform similar experiments and reflected to the experience of Phase 1 earlier in the school year. Once Harry allowed his students the independence and abundance of time to investigate Collision Theory on their own, it was obvious that the students made decisions, negotiated within their teams, stood critically against chemistry and the practices in the classroom.

Regarding student attitudes to the proposed practices, the overarching conclusion from the observations is that for successful critical thinking students ought to be eased in the practices that help them build questions, explanations and arguments. As argued in the CT literature, time is a factor that cannot be overlooked, CT is an exercise that cannot be rushed. In the groups that participated actively with CT implementations, the different durations of the studies had different effects. The longer study indeed presented results that are more consistent: students gave explanations more frequently, voluntarily and with more confidence, they challenged each other, corrected and self-corrected. The observed shift in the classroom practice from the first class visit to the last was how much more time students spent engaged in class team activities that required interaction and concentration. Though Hannah provided encouragement till the last day, the instances that students provided reasoning without being asked for it increased.

Reflecting on student criticism regarding learning science, an unappealing aspect was the hard-facts approach of learning without room for disproof, for changing the wording of definitions, for discussion of different viewpoints that students may come up with (Osborne and Collins, 2001, p. 452). In response, two of the participating groups in the study presented quite a different classroom picture with a lot of student activity and self-regulated learning countering the criticism and proving that once chemistry became an interchangeable science with room for theorising based on concrete blocks of knowledge, student perception changed in favour of learning chemistry. Activating student participation by asking for or building towards questions, explanations and arguments was the motive for thinking through their actions, descriptions, supporting data and quoted evidence, inferring from the classroom activities that inactive student participants cannot claim to be developing CT skills by observation. Acton and interaction are required.

6.4 Key themes and limitations

Besides the focal points of the research questions that framed the philosophy, design and implementation of the study, themes not included in the design emerged during the school visits. In the literature, cognitive acceleration offered an insight of studies enhancing students' understanding of the sciences. Post-analysis and with reflection on the pillars of CASE, parallels can be drawn between CASE and the way dialogical practices had a positive effect on establishing concrete blocks and strengthening students' reflection and active thinking (sections 6.4.1). Additionally, School 1 had a culture of collaborative CPD and the teacher collaboration offered the participating teachers the opportunity to reflect, present and explain their practices outside the study, which had a positive influence on the study (section 6.4.2). Finally, due to the different timelines for the participating groups, combined with the fact that time is a reference in the overviewed literatures, time as an influencing factor is highlighted for its positive and negative effects (section 6.4.3).

6.4.1 Establishing concrete blocks through dialogical classroom practice

Adey (1988) described the concept of cognitive acceleration as a method of enhancing the students' cognitive development. The concrete contexts (Adey, 1988, p.127) lent themselves as a way of cementing the connection of the RQs to the results. Adey (1988) talked about helping students familiarise themselves with certain concepts first. Familiarity in this study came with the use of dialogical classroom learning, in the form of in-class tasks and experiments that had to be talked about, negotiated and completed. This had the form of structured discussions within small group of peers, which according to Wellington and Ireson (2018) help students understand the nature of science. The success of the practice in the instances quoted and many other unquoted was largely due to engaging students to participate in these actions together rather than expecting them to come to a conclusion based solely on individual work, study and understanding. Embarking on an investigation/question as a lesson objective provided what Ennis (1996a) defined to be Focus, in his FRISCO model for developing critical thinking, and additionally embarking on it collaboratively, agreed with Paul's (1990) perception of the educational application of CT. This dialogical classroom practice (also supported in the literature) benefitted participants by establishing and frequenting peer communication channels, thus accustoming the students to verbalising their thoughts and making them more confident expressing their ideas. The teacher contributions in these instances were also encouraging with clarification/prompting questions, challenging questions or comments, utterances of encouragement or praise, comments directing to the right answer without giving it, according to study suggestions. The APhA definition for critical thinking in education mentioned the ability to contextualise considerations, which in the context of the study was actioned by the teachers. In this instance, the repeated in-class collaborative tasks created the context for students to establish concrete blocks thus helping them create their own criteria for accepting or rejecting evidence/opinions.

Though the conceptual framework of the study did not include the concept of dialogical practices, the set-up for suggested practices urged teachers to encourage their students to actively participate with opinions in the lessons. In the literature, dialogical teaching practices enhanced the student participation in science education (SE). Those often related to explaining (i.e. Chin, 2006) or argument building (i.e. Newton et al., 1999). In the practices that were advised and those implemented, dialogical exchange was a necessary component for the purpose of augmenting student contributions in the lesson to normalise explanations in the lesson flow. Once the dialogical culture established in the classrooms, observations saw students actively listening to one another and engaging in meaning-making discussions, Q&As, debates.

What my findings add to the existing literature is evidence that dialogical practices are necessary when teachers wish to encourage their students to actively participate in the lessons. In these practices, students need structure that is provided by organising an investigation (also expressed in Osborne and Collins, 2010). The effectiveness of organising an investigation within the CT context, in the analysis presented (Chapter 5) showed that in the absence of dialogical practices the schema of the scientific method (Wellington & Ireson, 2018, Picture 2, p.46) was disrupted at several points, because student understanding relied solely on individual work and the discussion which led in negotiation of terms and understanding that was observed in Group 1, for instance, was missing in Group 2. Further to this, the dialogical practices in the analysis did not rely heavily on spontaneous student questioning. This had to be implemented in the lesson plan. However, not having peer questions did not impede the communication of the students as was found by King (1994) and Graesser and Person (1994). In fact, when left to make their own decisions about their communication students, especially the younger ones, did not opt for questions rather for exchanging explanations with one another, reciting information they knew and discussing how they understood it. Because of the dialogical practice and the exchange of explanations leading to established concrete blocks of knowledge, when the teacher posed questions, students provided answers more readily cancelling the psychological factor of hesitation (Maskill & de Jesus, 1997) without diminishing effective communication necessary for students to take responsibility of their learning (Crawford et al., 1998).

6.4.2 Teacher collaboration

The teacher collaboration manifested itself in two ways: one was the level of commitment that teachers showed in implementing the suggested practices in the classroom, which immediately affected the study, the observations and the results. Observing the teacher efforts to action the implementations was in itself data that depicted the reality of an ethnographic study. The three Groups had different levels of involvement following the rhythm set by their teachers. Hannah engaged with conviction and persistence, made time for planning and reflecting interviews and invested on the suggested as well as her own ideas in the 7 weeks of the research and at the end of the school year for the final reflective interviews. In Hannah’s participation we see in application Paul's (1990) suggested commitment in practicing critical thinking in education. One of Paul's (1990) key directives was that the teacher ought to help the students learn how to participate more actively, to create those opportunities for them to express their ideas. Hannah was the participant that embraced the concept of critical thinking, appreciated the philosophical dimension and understood the need to research effective classroom practices. She also showed she understood the meaning of context (supported by McPeck, but disputed by Halpern, for instance). But Hannah's participation was an active exercise of critical thinking for herself, because she did not shy away from critically assessing the practices, re-evaluating outcomes, driving the discovery in the research by asking many questions (as investigated by Stevens, Chin, Cotton and so on) but thus offering a platform for student explanations.

Samantha expressed confusion and doubt about the successful implementation of CT exercises, she was sceptical regarding whether the proposed practices would impact her students and she eventually opted to forego experimenting with the suggested practices. Instead, she discussed and debated the value of critical thinking as a learning aim for secondary chemistry education, arguing that the students' young age was an inhibiting factor. The interest in Samantha's participation was in the fact that she recognised the value of critical thinking in science, she saw herself as a competent critical thinker, but she could not see the place for it in her practice, which possibly many chemistry teachers might agree with. Samantha's outlook on CT was that it failed to obviously connect to successful learning practices that were proposed by Chin, for instance, with her work on questions, or prompting student explanation (longer than a single-word answer) that helped engage students with the content of chemistry and making meaning (Osborne and Collins, 2001; Ogborn et al, 1996; Mortimer and Scott, 2003; Wellington & Ireson, 2018).

Harry had research training and in the suggested practices he saw the opportunity to train his students' research skills: analysis, evaluation, reflection and so on. From the first meetings he embraced the idea of differentiated experiments for his cohort and organised them accordingly. He could see the value of setting experiments with varied results in order to drive student interactions to communicate experimental results and follow the loop in Wellington and Ireson's (2018) scientific method (Picture 1, p. 46). When Mary, the student-teacher, joined the project, she was also positively predisposed, though inexperience made her feel anxious in regards of performance. Mary often found the suggested practices challenging because she had to reconcile her training process with an implementation she had not made provision for in her lesson designs, though the study outcomes were similar to the lesson outcomes. By her own admission, Mary provided lengthy explanations to her students, which deprived them of the opportunity to think for themselves, analyse, synthesise, apply (Paul, 1990, p. 233). From the viewpoint of the study it was an opportunity to find the strengths and weaknesses of the suggestions and instructions with someone new to the profession. Upon reflection of suggested practices that were used by Mary, her struggle – as is often with initial teachers – was to pass explaining concepts and theories over to the students rather than over-explain phenomena herself. The challenge was how to navigate through speaking less and still covering the lesson content. The reflections suggested that in the occasion of an initial teacher using CT-oriented practices, a more frequent review of the aims and methods for critical thinking opportunities would possibly be more helpful to the teacher. Here, Hannah's practice of bouncing student questions back to the students might have helped Mary to ask those questions that Stevens (1912) credited to the "scientific teacher" (p.4) and which motivated Hannah's group to narrate their thought to get to the answer.

The other way teacher collaboration entered the study was when the teachers in School 1 organised CPDs sessions for the science department in order to share best practices that were outcomes of participating in the study. This happened during the visits with Group 1 but after Phase 1 with Group 3 had ended. Hannah and Theresa – Deputy Head and Head of Science in School 1 respectively – led a science department where good practice was shared and they both felt that the investment in critical thinking skills would and should benefit the science department. Collaboration between teachers was explicitly expected and practices were openly discussed. The model for sharing practices in School 1 also followed the teacher development cycle of planning – trying – reflecting – discussing and planning again (Monk & Dillon, 1995, p. 3). Although inter-teacher collaboration was not in the conceptual framework, the idea appeared to benefit the practices. Hannah presented and discussed with her colleagues the CT practices she had implemented successfully. According to the framework, this was the reflective device that Hannah created for herself revisiting and reflecting on successful and challenging practices by sharing them with her colleagues. In the duration of the studies, the teachers used the reflective and planning interviews with the researcher to gauge results and recognise practices that worked or did not work and these discussions informed the CPD sessions. Teachers used these reflective discussions with the researcher to get a point of view of an informed observer practicing informal critical reflection and enhancing their understanding of CT and keeping an open mind (Dewey, 1933; Ennis, 1962, 1964, 1996a; Facione, 1990).

A lesson learned from the teacher collaboration, is that implemented practices were more successful where reflective discussions were more frequent. Though most of the CT literature emphasises the importance of the individual remaining rigorous in practicing CT skills and developing a disposition of fairness and open-mindedness to foster the establishment of a critical thinking module, there is little said in terms of collaborative reflection. In the literature the critical thinker uses their own faculties to reflect, whereas in the science education context present in this study, the reflection was a collaborative effort where practices were discussed with the researcher primary but also with the Head of Science (School 1 only) and within CPD.

6.4.3 The time factor

Even though in the literature it is not explicitly stated, it is implied that to develop as a critical thinker is a process of rigorous exercise of skills, reflection on disposition, which is also closely dependent on the factor of time. The different durations of the studies for Group 1 and group 3, however, allowed us to observe how the factor of time affected the development of students' critical thinking skills (though not dispositions, as mentioned in Section 5.2 and all the sub-sections 5.2.1-5). Paul (1990) discussed perseverance from the teachers in practices of CT, Ennis (1996a) made it clear that time references had crucial impact in the perception of evidence and statements, Siegel (2010) spoke about education as a perpetual vessel for CT. Time dependence refers to long term and renewed/reviewed practice of skills on different aspects of education and indeed life. The expectation that an individual's CT skills will develop at the end of a course (as was the outlook of CT assessment, Section 2.5.2) or after a fixed term of time has been challenged in Chapter 2 and the conclusion is that the longer the individual practices the more experience they accumulate, and CT skills are sharpened. This has also been implied in the CT framework (section 6.3) where repetitions are looped in a manner that requires returning to the initial point to re-investigate where the process went wrong and on reflection of the literature, it is also in the reiterations of evidence in the scientific method of Wellington and Ireson (2018). The observations of the groups and the teachers supported the claim that time was a significant factor affecting the extent of manifestation of results.

For Group 2, which had the shortest observations plan and the most contained input little can be said. Samantha taught the syllabus in segmented units and compartmentalised the module to help her students grasp the content. This practice fragmented timelines as per unit and broke the continuity of the learning. It did not affect positively retention of information because the building blocks were repeated and revisited in the same lesson but not across lessons. Interestingly, reading the science curricula for Key Stages 3 and 4, a continuum was detected of repeating the information with more scientific detail as the students progressed in the school years with the purpose to establish the scientific method of working as well as understanding science (DfE, 2013b; 2014b). Linking this back to Group 2 and the observations gathered there, the time of observations was short and no dialogical practices were adopted. The collaboration and interaction within the study remained to teacher-researcher level. The student potentials for CT, therefore, could only be attributed to students' dispositions, though the few visits with Group 2 could not justify a concrete conclusion.

Group 1 was the most educational in the study. It was the longest participating group on a continuum stretching over 7 weeks of lessons – 10 weeks including vacation time – and the results were gradual and positive. Hannah gradually came to familiarise herself with effective practices of scavenging student explanations, using questions or prompts helping students' self-expression (Paul, 1990). She quickly started relying on in-class task getting students to practice the atomic theory and generate enough data for them to recognise the patterns in the Periodic Table (Wellington & Ireson, 2018; Taber, 2012; Woodruff & Meyer, 1997). These were concrete blocks of knowledge that had a relatively quick turn-around of learning in terms of time. She also persevered inserting new ideas and refreshed activities in her practice. Hannah's students were the group that was most consistently exposed to opportunities for reasoning, thought provoking, and reflection and the recorded results improved over time. As the students grew in confidence for asking questions, providing answers and supporting their tentative theories, the link of Qs, Es, and As – which originally did not go beyond Q&E – gave way to enriched interactions and a holistic practice, not only from the teaching viewpoint but also from the learning one, which informed the framework. This was also discussed in McNeill and Krajcik (2008) who claimed that explanations helped in the retention of science content and I Chin (2006) who used Qs and Es to promote higher order thinking and expression in science education.

The holistic approach with Group 1 was not in place from the first lesson. Instead in the first few lessons implemented practices were under the advisement from the study and the teacher reflected with the researcher to conceptualise why and how the suggested practice helped towards CT. This quickly changed to the re-dressed practice of engaging students in collaborative tasks where they discussed their explanations of phenomena with their peers. Time was essential for this shift that mostly affected the students in their learning practices. It also showed that the looping process of re-iterating the same content over a number of lessons helped both the teacher to reflect on the CT practices and the students to return to their knowledge with a more experienced outlook (also analysed in Section 6.2). Habitually discussing the tasks and the outcomes developed student contributions from one-word answers to expressions of reasoning behind occurring phenomena (Chin, 2006). The first well-formed explanations were recorded in Lesson 4 during the students' presentations, and the first argument was also observed during that lesson. More instances of students verbalising their reflection processes and the outcomes were observed in later lesson (i.e. Quote 17 – Lesson 10, Quote 45 – Lesson 12, Quote 47 – Lesson 12). In the duration of the study, the student contributions changed both in frequency and content. The group was competing to offer their opinions during the lesson, but also, we witnessed students coming to the realisation of theories behind phenomena on their own. Quotes 45 and 47 were characteristic demonstrations of students actively reflecting upon their knowledge and practice to provide reasoning behind their actions, interactions and the production of an explanation.

Group 3 had the chance to practice the experiments in Phase 1 of observations, which was more structured, to propel curiosity over different sets of results and peer discussion. Despite the use of a more structured study to accentuate observations of differences in the experiments and motivate student interactions, the span of two weeks was not enough to fully achieve these goals showing that the influence of the proposed structured practices (Wellington and Ireson, 2018) was proportionate of time. The more students practiced the more comptent they became. With this group, it was noted that time was a factor that also affected the teachers. Hannah, for instance, had the luxury to reflect on a number of lessons and re-attempt and adjust her practice. Harry and Mary did not have the same opportunity. The time scale in this case, affected the teachers as well as the students. Compensation for the rush of time with Group 3 was attributed to the more mature age of the students who quickly adapted to the change of content and engaged in the planned investigations. Beyond the peer discussions that remained shallow for the most part, Group 3 responded very positively in the reflective discussion in Lesson 4. By Lesson 4, the students had heard about collisions in liquids and had experimented with different factors that affected the rate of reaction. Had more weeks been added to investigations with Group 3, a richer dataset was projected.

The influence of time was also reviewed in a different way with Group 3. Having two Phases of observations had the advantage of observing how the group behaved in Phase 2. The students conducted the same experiments but for an extended period in Phase 2 and the observations were of great interest. During Phase 2, the teacher and students were not rushed to finish the experiments and had the chance to investigate different factors each time, i.e. reactants, temperature, emitted gas over time. The students showed confidence and understanding of the workings of the experiments, team collaborations worked well and rapport developed within the teams while conducting the experiments. The teacher attitude was also different as the teacher's instruction was for students to take their time and observe what was happening. According to Harry, the fact that the students were already familiar with this set of experiments had a positive effect on their confidence performing them. Students often connected their actions to processes from Phase 1. Despite the time lapse, the success of the second round of the experiments was due to the mishaps from Phase 1. Students were more aware of what could go wrong, therefore they were more careful in applying processes and hypothesising expected outcomes as well as potential explanations in the event of a non-result.

In hindsight from the experiments of Phase 1, the students were able to stand more critically against both the experiments and their own conduct while performing them. Though Phase 1 and Phase 2 were three months apart, during which time there was no research input, Phase 1 had a positive aftermath effect on the performance of the students during Phase 2 both in terms of performing an experiment as well as in using critical skills to observe and explain the mechanisms of their work. The expectation that the structured input of Phase 1 would insert opportunities for critical thinking was not realised, it did, however, create valuable experience to propel critical thinking in Phase 2, which the time interval fuelled rather than cancelled.

My findings from taking into account the factor of time in the study show that we cannot expect students to develop critical thinking unless teachers engage in teaching chemistry in ways that allow time for students to:

(1) build their building blocks of knowledge (Adey, 1999),

(2) overcome hesitation of being exposed when offering explanations (Maskill & de Jesus, 1997; Bolter et al., 2013; Mamlok et al., 2015),

(3) become accustomed to expressing their frame of thinking in deep explanations (Osborne & Collins, 2001; Chin, 2006) and possibly arguments (Duschl and Osborne, 2002; Mortimer and Scott, 2003; Toulmin, 2003; Kuhn, 1992).

Quote 45 was an educational moment for the research as well, having a student prove that the way lessons were designed did not follow the same time progression that the ideas developed in the thinking of the students. We expected students to express their understanding in the lesson that we designed for conceptualising electro-reactivity but that actually developed when students had time to reflect on the exercises and manifest it in later lessons. It was futile to believe that the students would fully grasp the specified content in the specified lesson, rather with re-iterations students showed us when they got to that point of deeper understanding by making references without being prompted.

6.5 CT-as-praxis: a definition for CT applications in the classroom

Defining critical thinking has been a consistent challenge in CT scholarship, as mentioned in Chapters 2 and 3. It was also a challenge for this study to establish the definition by which critical thinking for classroom applications would best frame the conceptual work as well as inform the participants-collaborators. Revisiting the definitions of seminal scholars and upon reflection of the study of CT in chemistry education, two symbiotic entities form. One is critical thinking as theory, a set of values that apply better to forming disposition. The other is critical thinking as praxis in the learning context where improvement is maximised in exercising skills. The definitions for critical thinking that the seminal scholars gave in their work attempted to capture both the practice as well as the noble philosophy, struggling to find the words that captured essence and practice in one complete definition. The main argument in the literature was if we put emphasis on the skills are we doing justice to the philosophical ethic of critical thinking, namely the disposition and the theory? On the other hand, when focusing on the theory, can we trust that cultivating the disposition ultimately fosters critical thinkers?

Favouring the APhA definition contextualised expectations for this study, informed the aims for the questions, explanations and arguments and shaped the investigative question in the conceptual framework. However, in practice, it left a lot to be desired regarding classroom praxis. The definition focuses more on describing the values a critical thinker ought to have, i.e. open-mindedness, willingness to acknowledge bias and reconsider the original premise, desire to learn the truth even at personal cost. The confusion arises from the brief description of the analytical skills, the set of criteria, the study of methodology – present in almost all theoretical definitions – but not evidently connected to the rest of the definition. In the analysis justifying the choice of this definition as the conceptual framework (p. 16), the distinction of two parts in the definition is made evident. It resulted in reconciling the literature conflict between disposition and skills and led to the metamorphosis of viewing disposition and skills as complementary to each other (section 2.4). Following that, in the practical part of the study, the classroom visits, the observations and the participant interviews, the APhA failed to identify pillars of good practice. In reflection, the APhA definition did not fail, it was merely misinterpreted to encompass all that was needed to support the study. Gaining knowledge from the study, however, this was recognised a CT-as-theory definition and the new need was to find a CT-as-praxis definition.

The successful classroom practices highlighted three missing references that rendered the APhA definition inadequate for describing the development of the critical thinker in the classroom. These were: (a) the role of the teachers, imminent for structuring and safeguarding the process, (b) the positive results of collaboration and dialogical classroom practice (also linked to empowering the students to be active and agile towards their CT development), (c) and the significant intermediate of reflective devices, ever-present in student-centric classroom practices but not valued as such. Specifically, at the early stage of framing CT in the chemistry classroom, the teachers contextualised considerations to enhance students' understanding of the content and context. The contextualisation required a learned, more experienced individual to set boundaries, which fell into the teacher roles. Chemistry as a subject for study offered the frame and (more importantly) the idiosyncrasy for critical thinking and – along with teacher-set boundaries – provided the material, guided the input and stratified the impart of the concrete blocks slowly building up both content (chemistry) and context (CT). At that early stage of implementing CT practices, the students could not rely on their individual work and understanding to form considerations. This was more noticeable with the younger participants who thrived in the collaborative tasks. Older students showed more competence for individual thinking, but nonetheless still became more thoughtful and critical when engaging in group discussions. Dialogical practices had positive impact as tasks set by the teachers aimed to motivate students to explore their thinking. Encouraging the content-relative banter nurtured the growth of the reflective devices, which gradually became an integral part of the process initiating an investigation, understanding and explaining it.

These impactful factors emerging from reflection on the data, design and themes were strongly interlinked and steered towards a CT-as-praxis definition:

Critical thinking in chemistry education is the process wherein dialogical classroom settings motivate students to engage in purposeful, self-regulatory thinking, which results in the interpretation, analysis, evaluation, and inference of data, facts, models and theory towards forming an assertion. The student critical thinker ought to be encouraged to remain inquisitive through investigative questions. Simultaneously they ought to be allowed to express doubt, opinion, false ideas, make comments, ask questions towards establishing own judgement using re-iterative reflective devices. Teacher encouragement for student explanations of evidential, conceptual, methodological, criteriological and contextual considerations offers the support and input that moulds assertions into sound judgements. The ultimate indication of developing critical thinking is the engagement of students in arguments trying to establish a prevailing theory for a phenomenon, while remaining open-minded to opposing opinions, honest in facing personal bias, well-informed, willing to reconsider, rigorous in selecting criteria, trustful of reason and persistent in entwining the practical and theoretical components of a chemical investigation.

This definition has resulted from the successful classroom practices and as such, it defines CT as a practice not as a theory. Unlike the theoretical definitions of critical thinking provided in the literature chapters (2 and 3), the definition of CT in the context of chemistry education clearly addresses critical thinking as a practice, as a classroom application of activities but does not describe specific applications. Description of applications would defeat the purpose of giving teachers the freedom to adjust or create classroom activities of their own. The aim of the definition for critical thinking as praxis is not to offer specific training schemes in the teaching of chemistry. The definition aims to provide guidance for teachers when using their own classroom practices to use them in a manner that fosters and augments critical thinking for the students – in a similar way that Taber (2012) compiles effective teaching approaches in *Teaching secondary chemistry*. The Q-E-A concept is important but not effective unless dialogue, student independence and fostering reflection are established. In the echo of the study, the described practices are offered as a guide but are not exhaustive, maintaining an open end for teachers to invent or re-invent practices that will give chemistry learning the edge of critical thinking. Challenging the literature about teaching chemistry using questions, explanations and arguments, unlike Chin, Duschl and Osborne, and Erduran, instead of investigating one element of scientific inquiry, we investigated three to establish firm links between the elements, the combination of which resulted in better critical thinking.

The study followed closely chemistry lessons; however, sciences have in common the interplay of theory and practice, the ideals of scientific inquiry, the inclination of examining facts for the explanation of phenomena. Despite the different laws and principles that imbue each science, the rigour of abiding by virtues of truthfulness, honesty, open-mindedness and trusting the data to guide to an opinion or judgement, is consistent in all sciences. In that light, the definition and framework for critical thinking in chemistry education could extend to apply to other sciences.

Summary

The discussion presented in Chapter 6 brought together the theory and practice of the study in an effort to highlight the strengths of the proposed practical implementations but also explore the weaknesses in a meaningful and constructive way. The lessons learned from the study were that it did not suffice to theorise that the students could think critically, evidence was needed for it, hence the need for students to ask questions, structure and express their explanations and prepare adequate data to argue their point of view when challenged. These student-generated verbal contributions were more likely to reveal the thinking pathway for the formation of the Q-E-A expressions. Critical thinking lay in the rigour these elements demanded in preparation. Though the study aimed to increase CT within the chemistry classroom, the final observation from this journey was that aiming at the development of critical thinking and aiming at teaching/learning chemistry were not two separate goals. One aided the other in an intertwined dynamic. Critical thinking forges good thinking skills which can impact positively better understanding in chemistry; chemistry, on the other hand, being an active theoretical and experiential science, offers a wonderfully appropriate environment to practice critical thinking. When learning chemistry, practice with exercises and problems brings improvement. Similarly, unless CT is practiced frequently and consistently, it will not flourish.

7.0 Conclusion

Chapter Objective

This is the last chapter has been organised in a way that presents the aspects of the study that were not coded and analysed from the theoretical model to the practice. These were specifically, the impact that independent, self-regulated learning practices could have in future research; and the positive influence of teamwork in building CT skills. There is special reference on the teachers' expectations concerning the influence that the study had on their students and how this has informed the research conducted. Moving forward, there are areas of the chemistry classroom life that could further contribute towards a critical thinking environment, practices that focus on a more consistent student participation and more coherent student-student interaction: (a) a community-of-practice/learning approach, and (b) an independent learning approach. These are explored to a reasonable extent in this chapter with the aim to lay foundations in theory and with the hope that they will be properly and practically explored in the classroom environment in the future.

7.1 Moving forward

Though the study was done in England the literature that is relevant to the skills under investigation shows that these aspects are universal and therefore applicable within different curricula and in different countries. A promising potential for further research to follow this study would be a multinational project wherein the proposed model would be implemented with the collaboration of teachers and students in a longitudinal study in school chemistry and possibly other school sciences. The experience of collaborating with teachers and the results of the study, which unanimously revealed the impact of teacher attitude towards the idea of critical thinking in the secondary chemistry classroom, calls for better educating teachers to boldly challenge traditional models and teaching practices in order to avoid guiding their students to a strictly structured, ready-made type of education that deprives them of the opportunity to develop their critical thinking abilities. From the literature and also from other not closely readings and interactions with people in education there was the strong impression that critical thinking is only one term that entails the components investigated in the present study. Terms such as higher order thinking, reflexive practice, high cognitive questioning, scientific inquiry all have in common certain thinking characteristics that contribute to criticality, skill development, and the nurturing of a certain disposition that can sustain those qualities. Practices and models that prescribe independent learning, the creation of a sense of community in the classroom, systems that motivate the students to be more active in their learning journeys in multiple ways (experiments, theory building, model conceptualisation, etc.) add colourfulness in both the practice that affects learning positively. Critical thinking as it was proposed in this study is one of the tools to be added to the pool of tools teachers have at their disposal to diversify their teaching. It is a powerful tool because it can help students develop better understanding, an insight for subjects that they may not have expert understanding in. Critical thinking may not be for every lesson or even the entire lesson, it should, however, be a feature in the class that the teacher can *recognise* and explore, and the student should feel comfortable using.

7.1.1 Self-study or Independence of Learning

In the three aspects of critical thinking that have been presented in Sections 3.3, 3.4, and 3.5 a degree of autonomy for the students to become activated in these activities has been highlighted repeatedly. The literatures that support the generation of questions by the students, the production of explanations, and the expression of arguments, invariably refer to students as active participants in the science lessons, participants that are given opportunities to elaborate on their thoughts and the expression of them. The aim of independence in learning has been a science education goal introduced in US and UK educational theory for over a decade. The National Science Education Standards in the USA (1996, p. 88), stated clearly “when teachers treat students as serious learners and serve as coaches rather than judges, students come to understand standards of good scientific practice”. Similarly, the National Curriculum for England in Science (DfES, 2004, p. 45) mentions teachers encouraging independent working skills with the aim to facilitate the framing of understanding key concepts of science and excite the students’ natural curiosity. Going through the mandatory science education, students should acquire scientific work habits that allow them to “*select, plan and carry out* the most appropriate types of scientific enquiries to test predictions, including identifying independent, dependent and control variables, where appropriate” (DfE, 2013, p. 4, my italics). The process of selecting, planning, and carrying out any investigation within science cannot be completed if students do not have the confidence to take charge of the design for an experiment or a research-based investigation.

Self-study or independent learning in the study were identified as tasks that promoted organising, puzzling together and explaining the task, debating or dealing with questions about it in interactions with peers or teachers. Self-study or independent learning were not included in the research questions for this study, however, from the overview of the literature and the observations of three different groups, the premise developed that the more self-study tasks the teachers offered, the more confident the students became in dealing with chemistry. Building on confidence, students might be better able to look for scientific explanations on their own, beyond the classroom setting, after the end of their formal education, if they develop a degree of independence and confidence in their investigative abilities. Marzano et al. (2001, from book summary) in their self-study guide explored nine specific ways that self-study can be successful: “(1) identifying similarities and differences (comparing, classifying, creating metaphors, and creating analogies); (2) summarizing and note taking; (3) reinforcing effort and providing recognition; (4) homework and practice; (5) representing knowledge (nonlinguistic representations); (6) learning groups (cooperative learning); (7) setting objectives and providing feedback; (8) generating and testing hypotheses (e.g., problem solving, and decision making); and (9) cues, questions, and advance organizers.” Many of these practises link directly to critical thinking skills, involve a considerable amount of mental exercise on hypothesising, evaluating, argument-building and reflection. An ideal chemistry lesson should guide students to become independent in their thinking and, extending that, independent in their learning.

7.1.2 Towards a Pseudo-authentic Chemistry Lab – The idea of Communities of Practice (CoP)

The suggested practice of forming learning groups (Marzano et al., 2001) resonates with the idea that forming a learning community within the classroom and is predicted to have positive influence on critical thinking. A community is more than a group as the interactions within a community ma include a number of groups. Specifically, the English curriculum incorporates experiments in the class as early as in Key Stages 1 and 2, (primary school) where students experiment with simple everyday materials to investigate what these materials would be best used for (DfE, 2013, p. 9). The design and performance of experiments becomes more systematic and sophisticated in Key Stages 3 and 4. Chemistry as a school subject provides formidable opportunities for hands-on learning that should impact positively the process of scientific inquiry, forming and investigation of questions and other skills. Research shows, however, that experiments do not have the effectiveness in learning that we expect them to have (Hofstein, Shore and Kipnis, 2004; Lunetta, 1998; Hodson, 1990 to mention a few), and that further intellectual resources should be invested for maximising the usefulness of the experiment in the classroom. The idea of the community aims to simulate scientific inquiry in the laboratory, in terms of exchanging views and brainstorming explanations while students conduct and observe their experiments. Chemistry, in that sense, offers a highly conducive scientific content suitable for this approach as considerable amount of learning is expected to happen in the process of experimenting.

Gunstone and Champagne (1990, pp. 177-8) argue that the experiments have little effect unless they are preceded and followed by discussion and reflection and arguably the environment of a CoP can offer that. Wenger defines communities of practice as those “formed by people who engage in a process of collective learning in a shared domain of human endeavor” (2006, p. 1). That definition alone describes the collaborative nature of the scientific fields as well as the classrooms. Though scientists are notoriously believed to work alone and isolated, in reality scientific developments, the formation of most theories in chemistry and other sciences would not exist today if scientists remained isolated. In fact, summit scientific meetings throughout time have become the arena for presentation and explanation of findings, often re-interpretation of evidence and argumentation for one or another theory. In the reality of school chemistry, a class is in every important essence a community of practice since all the class participants commit to making an effort to understand what chemistry is and how it affects the world. It is also stated as a curriculum aim that school science in the final years of mandatory education aims to provide enough input for students to be able to make sense of the world and social progress based on scientific achievements (DfE, 2013, p. 2; DfE, 2014, p. 3).

Arguably, a classroom is already a community in many ways. However, education depends heavily on assessment of individual students and often teamwork and collaboration are frowned upon, thus breaking up the environment of community. On the other hand, a learning community wherein practice across related fields would make up the learning strategy has existed for a long time. As a more consistent pool for learning, however, it developed in the last two decades in the world of business and was greatly enabled by the development of the World Wide Web. Lave and Wenger (1991) were the first to introduce the term “Communities of Practice”. The authors’ theory about Legitimate Peripheral Learning focused around learning that happened within a practice (Lave and Wenger, 1991, p.35). Though the approach was psychology-heavy and this study has disclaimed expertise in a psychology background, the value of the theory lies in the fact that chemistry even at as early a level as secondary education can have a highly practical component.

In relation to critical thinking, one could claim that there is no obvious benefit participating in a Community of Practice since the exercise of CT is an individual process. However, as argued earlier and concluded in the findings, the development of the students’ understanding of chemistry relied heavily on the classroom interactions, the questions, the explanations, the arguments, the independent work and the combination of individual resources in a group experiment or assignment. For instance, the nature of the argument in science requires the existence of two parties, since it is an exchange that seeks to establish the components of the scientific structure that can best sustain and explain the scientific evidence. The argument in that sense is not one of “war that seeks to establish a winner” (Duschl and Osborne, 2002, p. 41) rather it is used by scientists as a tool to make their hypotheses both heard and understood within the scientific community. Not only that, but the scientific tradition is immersed in the practice of testing proposed hypotheses of others for validity and generalisability. This is the reason why the scientific argument makes most sense when presented in a community. The community can then participate in the testing and reflection process to either prove or disprove the hypothesis. In a parallel function, a classroom of peers has all the necessary characteristics to be a CoP and create the space for argumentation to develop.

Duschl and Osborne (2002) support the CoP as an environment within which student engagement with science can be maximised. In their view, a Community of Practice motivates justification, enquiry, the evaluation of individual reasoning as well as the reasoning of the peers (2002, p. 43). Given that chemistry learning relies principally on understanding key concepts and applying them on new context to gather evidence, the intellectual work required need be externalised and reflected upon and the CoP space where all participants contribute equally, under the guidance of teacher expertise, adds to the values of open-mindedness and spontaneous peer collaboration. Outside the CoP philosophy, the lesson of chemistry is very likely to motivate weaker students to seek the advice and collaboration of their more competent peers, when there is pressure for an answer or solving a problem. The relationship of this exchange, however, is one wherein one students asks another for the correct answer, not the reasoning of the answer. Adopting a CoP attitude could attribute to the consistency of the sense of contribution in a team and thus change the dynamic between more able and lesser able students. It “make[s] scientific thinking and reasoning visible,” propelling the CoP members to contribute, thus distributing the responsibility to all participants to stay active and productive (Duschl & Osborne, 2002, p. 44). Explanations and arguments have the potential to become the more frequent type of student participation which could motivate even weak students to engage more actively in the learning process. Examples of this were observed in the study, but as the focus was on the CT skills, this venue was not investigated.

7.1.3 The Embedded Challenges of Inadequate Scientific Literacy

One inhibiting factor that possibly contributes to students not offering explanations more frequently is their inexperience in using the right vocabulary (Duschl and Osborne, 2002, p. 40). By the age of 13 or 14, students have been learning chemistry in a formal setting for two years and are possibly familiar with the proper terminology but not yet confident in using it. In addition, the teacher is rarely in excess of time, which means they cannot afford to devote entire lessons to demonstrate and teach students how to properly express themselves using scientific terms. Even if the time was less of a constraint, dedicating lessons for scientific language specifically would not enter the top priorities of the science teacher. The way teachers are trained both in science and in pedagogy for science, there is clear focus on the content and the language aspect is more a persistent occurrence during the teaching rather than a proper component making up part of lessons. That element adds to the hesitation of the students to offer lengthy explanations.

It could be argued that the lack of dedicated teaching to scientific language amplifies stress in learning as students do not merely need to understand and learn the content but also a new language to communicate both the content and their understanding. Duschl and Osborne believe that adding language exercises in the science teaching practices can impact the learning and understanding of arguments to a significant extent (2002, p. 40). In terms of critical thinking, when students become more competent users of technical language, it sustains their understanding of the field and a prolonged practice in using scientific language regularly and properly builds up the experience, retention and facilitation of handling science topics with ease. Acquiring scientific literacy could aspire to a longer-term goal of being able to think critically in adulthood.

Epilogue

This study has been a journey of discovery about critical thinking and the place it may have in secondary chemistry education. It was necessary to first discover what critical thinking in education is and how it can be transferred to a practice. CT has a fundamental theoretical and rather abstract quality as a concept and as an internal process, only parts of which are manifested. Therefore, inserting critical thinking in school practice is a complex task. Critical thinking as a practice is desirable in tertiary education and there is considerable room and effort invested for growth in primary education. In secondary education, learning to develop as a critical thinker seems to become an implicit rather than explicit priority in teaching and policy making. That means experts know it is necessary, however the expectation is that the students will somehow become critical thinkers through learning chemistry – or generally science – without specifically designed input for CT. Content, curriculum, and syllabus become a main priority towards good assessment scores for effective education systems.

Moving from theory to applications in the chemistry classroom within this study, however, proved that critical thinking need not be separate from the teaching practice or the learning goals. Indeed, when kept separate, it did not bare results. Teachers need support to become aware of CT instances they can utilise to make students approach chemistry more critically. Chemistry specifically was seen as a prime example for CT opportunities because as a science it has fewer tangible components, describing the micro-world, particles that cannot be seen. It requires the use of models, patterns, and prediction of outcomes. It further builds on explanations of procedures, results, and unexpected products. It relies heavily on mental processes to successfully model, recognise patterns, and predict outcomes. It is not a memorisation science, rather a comprehensive science.

The study had inherent challenges: devising a type of measurement for critical thinking, while simultaneously considering measurement for CT to be flawed as a concept; finding and implementing a methodological identity; understanding the intricacies of doing school-based research where the observed variables are not controlled and are mostly interdependent; finding the nature of that interdependency. There were aspects which could be better designed and executed in the research; however, the journey for critical thinking in chemistry education would have failed, if upon critical reflection everything had worked perfectly. Looking forward, there are new aspects of education research that need to be explored with more confidence and accentuated critical and research skills.

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Appendix 1 – Observation Sheet used in the study

Original FIAC

Adjusted observation grid and codes of action

Date:		Teacher:		Class:	Year 9 Year 10	FIAC Adjusted
Time	Action	Time	Action	Time	Action	
0:00		20:00		40:00		Teacher Talk: Response 1. Praising & encouraging: when Ss active in lesson 2. Accepting, using, encouraging Ss' ideas: uses Ss' ideas as the initial point of discussion, by asking clarification questions and encouraging other Ss to ask clarification questions 3. Asking questions: when conversation/analysis of a phenomenon seems to be silencing the Ss, the T asks questions to propel conversation to start again (and follow-up questions if it is necessary). Teacher Talk: Initiation 4. Lecturing: T does all the talking and dissemination of information 5. Giving directions: Ss expected to comply with Student Talk: Response 6. Responding to T's questions, (a) raising their hand as a "yes" 7. Responding to fellow Ss: responses to other Ss' comments/questions, S-S interaction of any kind Student Talk: Initiation 8. Initiating: (a) asking qs to T, (b) asking for clarification, (c) presenting information they have gathered/ prepared, (d) performing an experiment, (e) asking questions to fellow Ss or any other action (lesson-related) that they may initiate Silence 9. Silence: pauses and short periods of silence after questions or discussion on relevant subject becomes difficult to sustain/group of Ss is weak & unwilling to contribute to the lesson 10. Silence while action: silence while performing an experiment or writing an exercise 11. Discussion irrelevant to the lesson
1:00		21:00		41:00		
2:00		22:00		42:00		
3:00		23:00		43:00		
4:00		24:00		44:00		
5:00		25:00		45:00		
6:00		26:00		46:00		
7:00		27:00		47:00		
8:00		28:00		48:00		
9:00		29:00		49:00		
10:00		30:00		50:00		
11:00		31:00		51:00		
12:00		32:00		52:00		
13:00		33:00		53:00		
14:00		34:00		54:00		
15:00		35:00		55:00		
16:00		36:00		56:00		
17:00		37:00		57:00		
18:00		38:00		58:00		
19:00		39:00		59:00		

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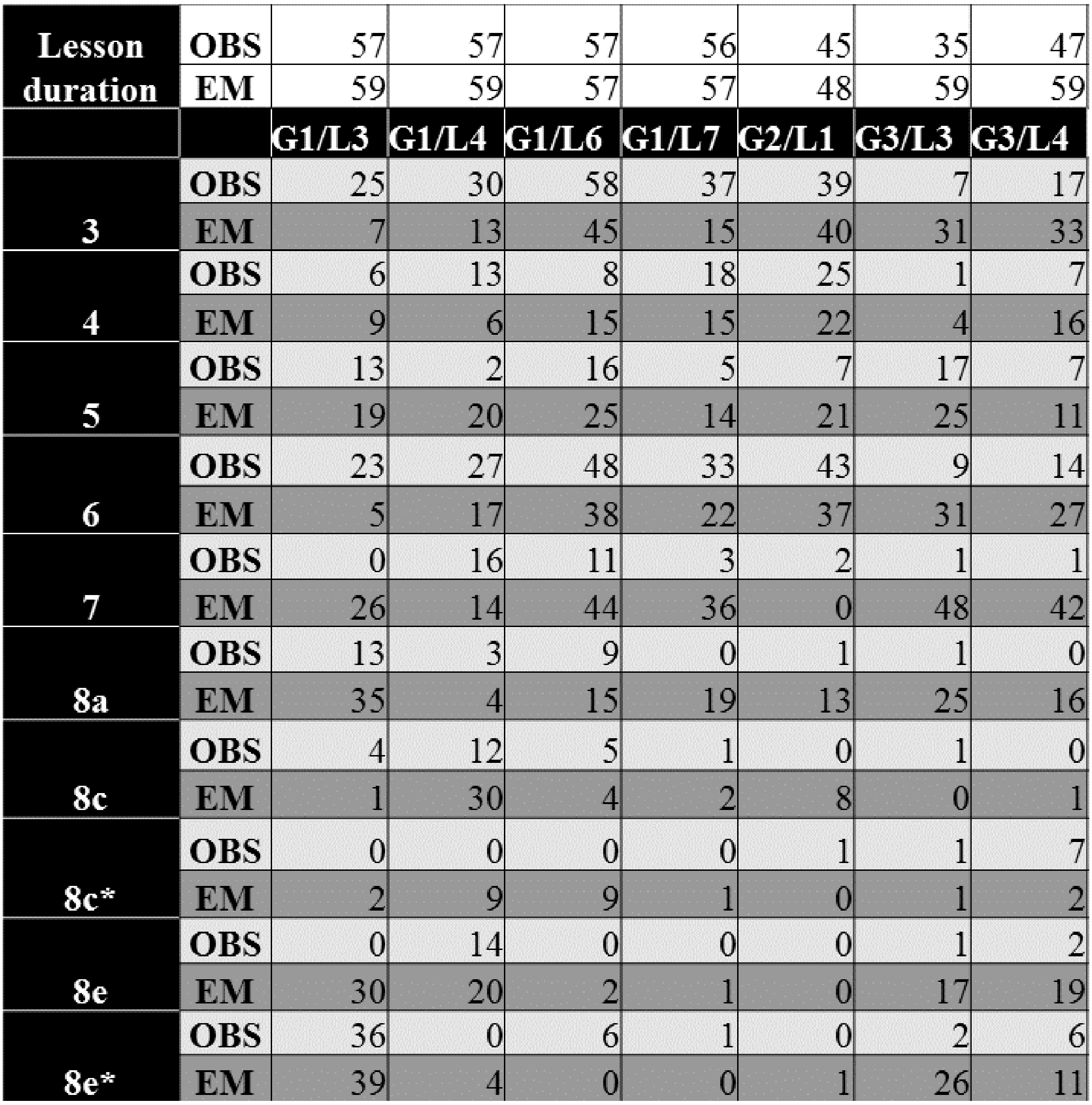
[1] 8a*: Ss asking Qs to Ss // 8c*: used when Ss encouraged by T // 8e*: used for peer conversation

[2] 10*: When Ss work noisily

Appendix 2 – Data from Observer and External Moderator

The table below shows the number of occurrences of the codes of interest that the observer (Obs) and the external moderator (EM) recorded during the school visits. The frequencies for Section 4.3.3 were calculated based on this data and the tendencies were drawn accordingly.



Lesson duration	**OBS**	57	57	57	56	45	35	47
	EM	59	59	57	57	48	59	59
		G1/L3	**G1/L4**	**G1/L6**	**G1/L7**	**G2/L1**	**G3/L3**	**G3/L4**
3	**OBS**	25	30	58	37	39	7	17
	EM	7	13	45	15	40	31	33
4	**OBS**	6	13	8	18	25	1	7
	EM	9	6	15	15	22	4	16
5	**OBS**	13	2	16	5	7	17	7
	EM	19	20	25	14	21	25	11
6	**OBS**	23	27	48	33	43	9	14
	EM	5	17	38	22	37	31	27
7	**OBS**	0	16	11	3	2	1	1
	EM	26	14	44	36	0	48	42
8a	**OBS**	13	3	9	0	1	1	0
	EM	35	4	15	19	13	25	16
8c	**OBS**	4	12	5	1	0	1	0
	EM	1	30	4	2	8	0	1
8c*	**OBS**	0	0	0	0	1	1	7
	EM	2	9	9	1	0	1	2
8e	**OBS**	0	14	0	0	0	1	2
	EM	30	20	2	1	0	17	19
8e*	**OBS**	36	0	6	1	0	2	6
	EM	39	4	0	0	1	26	11

Appendix 3 – Example of Module for Critical Thinking

Appendix 4 – Questionnaire for students of Group 3

Q1: Are you good at chemistry? Do you understand chemistry? Do you enjoy it?

Q2: How often do you find opportunities to express your opinion in the lesson? How often do you take opportunities to participate in the lesson?

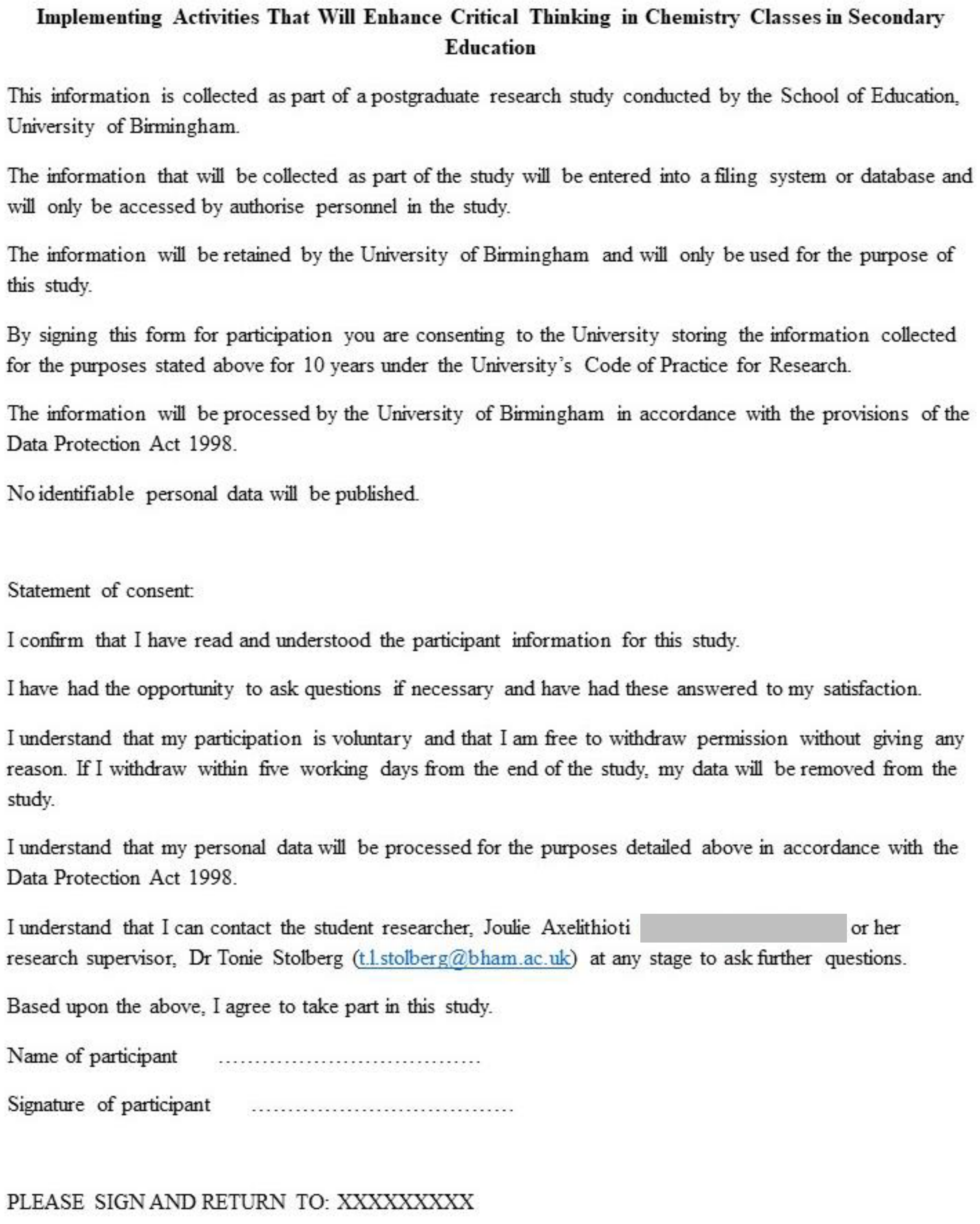
Q3: What do you do when you are not sure about an answer or an experiment?

Q4: Does chemistry make you feel that you want to explore things outside the classroom? Can you give me an example?

Appendix 5 – W-GCTA test – Inference

The Watson-Glaser Critical Thinking Assessment assesses separately each of the five components of Arguments, Assumptions, Deductions, Inferences, and Interpretations. Below the Inference assessment questions are given.

Appendix 6 – Information sheets and Consent Forms for participants



Implementing Activities That Will Enhance Critical Thinking in Chemistry Classes in Secondary Education

This information is collected as part of a postgraduate research study conducted by the School of Education, University of Birmingham.

The information that will be collected as part of the study will be entered into a filing system or database and will only be accessed by authorise personnel in the study.

The information will be retained by the University of Birmingham and will only be used for the purpose of this study.

By signing this form for participation you are consenting to the University storing the information collected for the purposes stated above for 10 years under the University's Code of Practice for Research.

The information will be processed by the University of Birmingham in accordance with the provisions of the Data Protection Act 1998.

No identifiable personal data will be published.

Statement of consent:

I confirm that I have read and understood the participant information for this study.

I have had the opportunity to ask questions if necessary and have had these answered to my satisfaction.

I understand that my participation is voluntary and that I am free to withdraw permission without giving any reason. If I withdraw within five working days from the end of the study, my data will be removed from the study.

I understand that my personal data will be processed for the purposes detailed above in accordance with the Data Protection Act 1998.

I understand that I can contact the student researcher, Joulie Axelithioti [redacted] or her research supervisor, Dr Tonie Stolberg (t.l.stolberg@bham.ac.uk) at any stage to ask further questions.

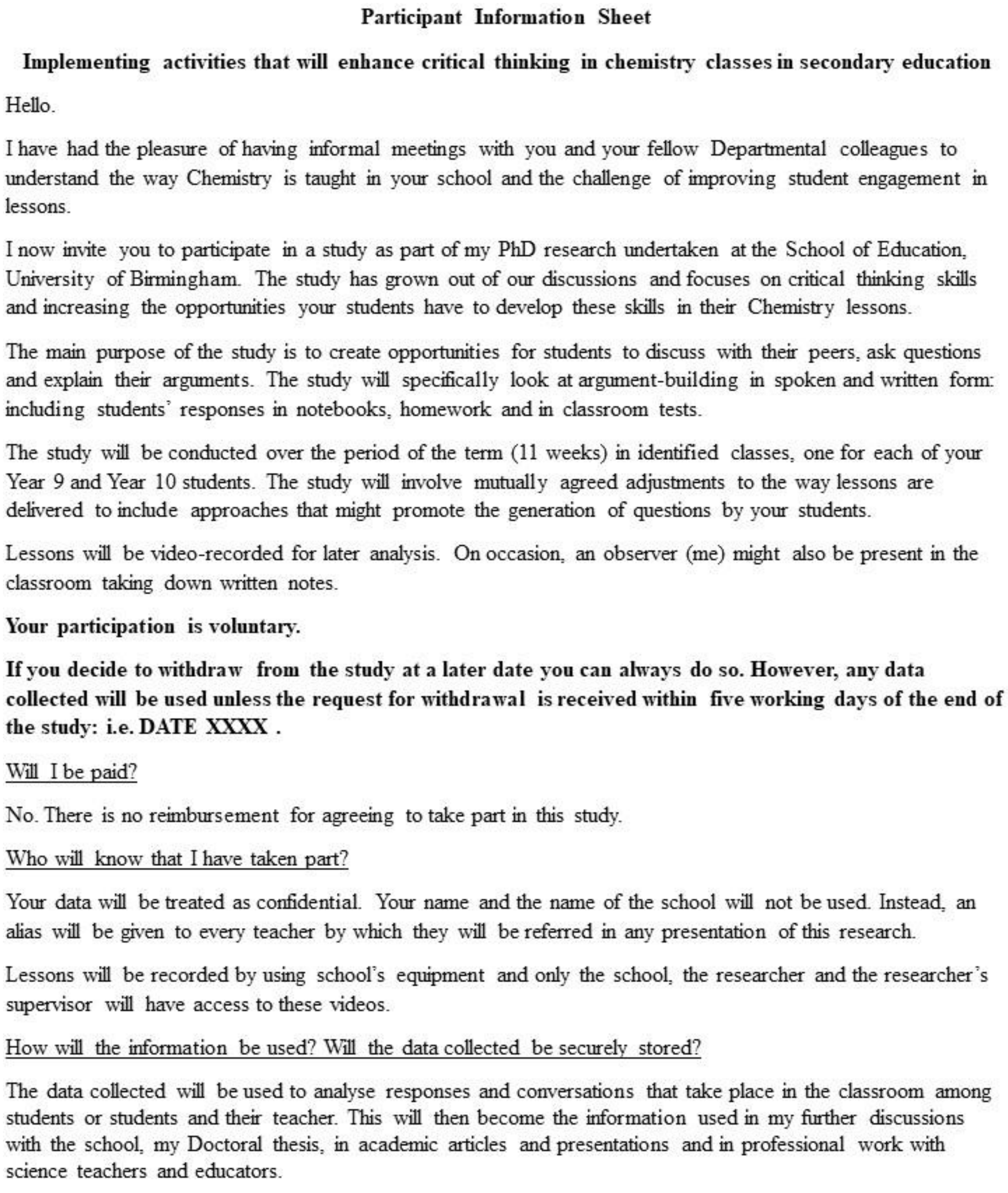
Based upon the above, I agree to take part in this study.

Name of participant ………………………………

Signature of participant ………………………………

PLEASE SIGN AND RETURN TO: XXXXXXXXX

Consent Form for the teacher participants



Participant Information Sheet

Implementing activities that will enhance critical thinking in chemistry classes in secondary education

Hello.

I have had the pleasure of having informal meetings with you and your fellow Departmental colleagues to understand the way Chemistry is taught in your school and the challenge of improving student engagement in lessons.

I now invite you to participate in a study as part of my PhD research undertaken at the School of Education, University of Birmingham. The study has grown out of our discussions and focuses on critical thinking skills and increasing the opportunities your students have to develop these skills in their Chemistry lessons.

The main purpose of the study is to create opportunities for students to discuss with their peers, ask questions and explain their arguments. The study will specifically look at argument-building in spoken and written form: including students' responses in notebooks, homework and in classroom tests.

The study will be conducted over the period of the term (11 weeks) in identified classes, one for each of your Year 9 and Year 10 students. The study will involve mutually agreed adjustments to the way lessons are delivered to include approaches that might promote the generation of questions by your students.

Lessons will be video-recorded for later analysis. On occasion, an observer (me) might also be present in the classroom taking down written notes.

Your participation is voluntary.

If you decide to withdraw from the study at a later date you can always do so. However, any data collected will be used unless the request for withdrawal is received within five working days of the end of the study: i.e. DATE XXXX .

Will I be paid?

No. There is no reimbursement for agreeing to take part in this study.

Who will know that I have taken part?

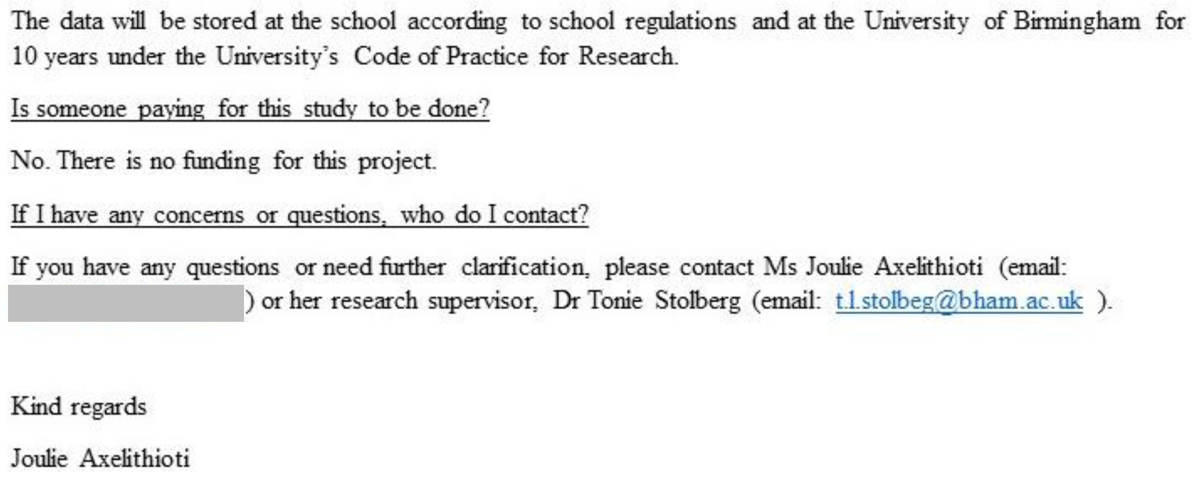
Your data will be treated as confidential. Your name and the name of the school will not be used. Instead, an alias will be given to every teacher by which they will be referred in any presentation of this research.

Lessons will be recorded by using school's equipment and only the school, the researcher and the researcher's supervisor will have access to these videos.

How will the information be used? Will the data collected be securely stored?

The data collected will be used to analyse responses and conversations that take place in the classroom among students or students and their teacher. This will then become the information used in my further discussions with the school, my Doctoral thesis, in academic articles and presentations and in professional work with science teachers and educators.

Information sheet for teacher participants, page 1



The data will be stored at the school according to school regulations and at the University of Birmingham for 10 years under the University's Code of Practice for Research.

Is someone paying for this study to be done?

No. There is no funding for this project.

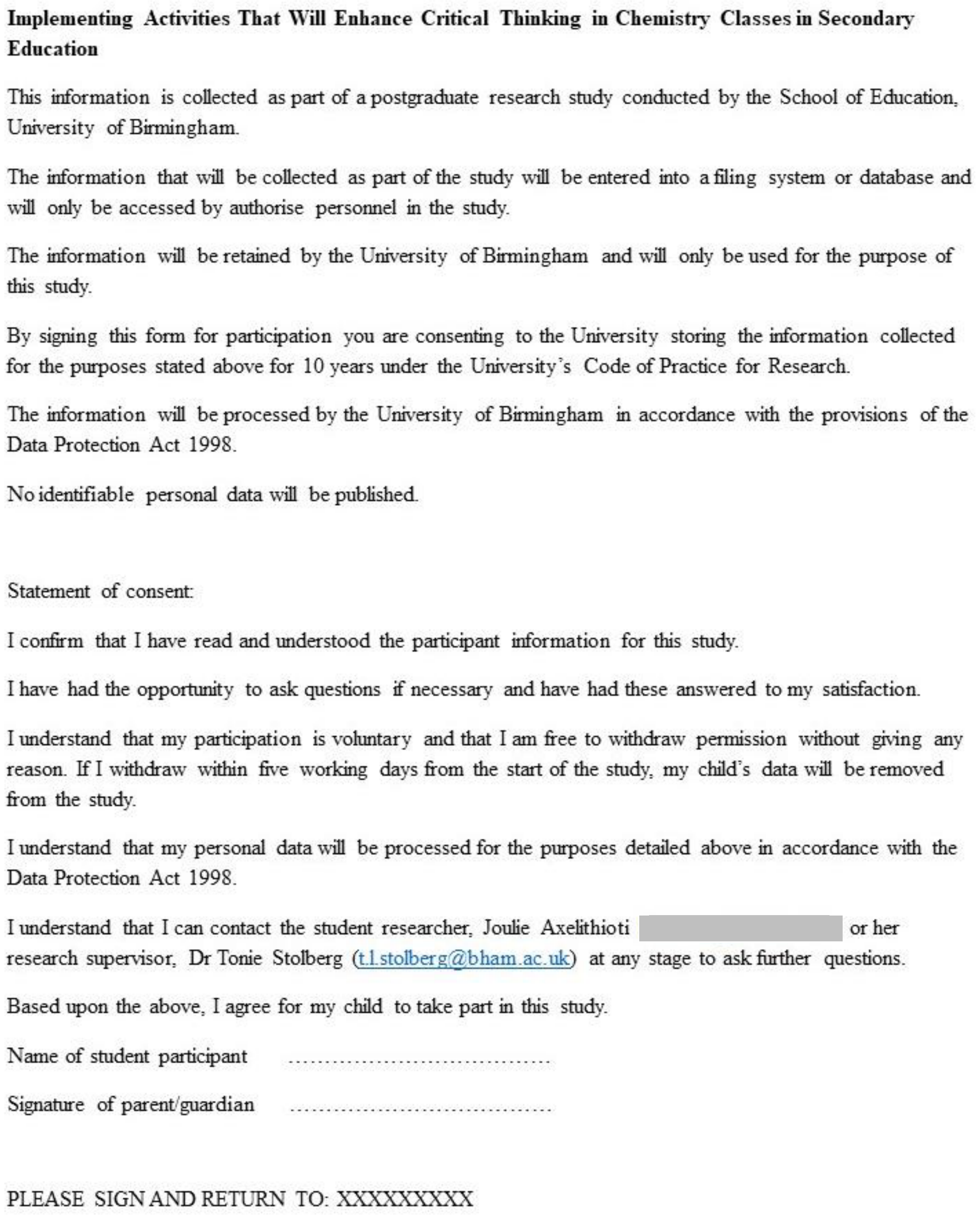
If I have any concerns or questions, who do I contact?

If you have any questions or need further clarification, please contact Ms Joulie Axelithioti (email: [redacted]) or her research supervisor, Dr Tonie Stolberg (email: t.l.stolbeg@bham.ac.uk).

Kind regards

Joulie Axelithioti

Information sheet for teacher participants, page 2



Implementing Activities That Will Enhance Critical Thinking in Chemistry Classes in Secondary Education

This information is collected as part of a postgraduate research study conducted by the School of Education, University of Birmingham.

The information that will be collected as part of the study will be entered into a filing system or database and will only be accessed by authorise personnel in the study.

The information will be retained by the University of Birmingham and will only be used for the purpose of this study.

By signing this form for participation you are consenting to the University storing the information collected for the purposes stated above for 10 years under the University's Code of Practice for Research.

The information will be processed by the University of Birmingham in accordance with the provisions of the Data Protection Act 1998.

No identifiable personal data will be published.

Statement of consent:

I confirm that I have read and understood the participant information for this study.

I have had the opportunity to ask questions if necessary and have had these answered to my satisfaction.

I understand that my participation is voluntary and that I am free to withdraw permission without giving any reason. If I withdraw within five working days from the start of the study, my child's data will be removed from the study.

I understand that my personal data will be processed for the purposes detailed above in accordance with the Data Protection Act 1998.

I understand that I can contact the student researcher, Joulie Axelithioti [redacted] or her research supervisor, Dr Tonie Stolberg (t.l.stolberg@bham.ac.uk) at any stage to ask further questions.

Based upon the above, I agree for my child to take part in this study.

Name of student participant ………………………………….

Signature of parent/guardian ………………………………….

PLEASE SIGN AND RETURN TO: XXXXXXXXX

Consent form for parents and guardians of student participants

Information Sheet for Parents and Guardians

Implementing activities that will enhance critical thinking in chemistry classes in secondary education

Hello. My name is Joulie Axelithioti and I am a postgraduate researcher at the University of Birmingham

I have had the pleasure of having informal meetings with teachers in the School's Science Department and in particular with regards to the way Chemistry is taught in the School.

I would now seek your permission your child to participate in a study which has grown out of these discussions and aims to see how students can get more out of their Chemistry lessons by giving them more opportunities to discuss some of the topics studied during the term.

What will happen?

To see what types of discussions take place in during Chemistry lessons this term, I will be present in some of the classes to note down what is happening and video recording classes over the term to ensure I don't miss anything!

Please be assured that I will not be noting the names of the children in the class and I won't be involved in assessing whether your child gets something right or wrong.

Similarly, the video recordings will be stored securely by the School and University and will only be seen by those involved in the research. They will not be used to penalise your child in any way.

Your child's participation is voluntary.

Is someone paying for this study to be done?

No. There is no funding for this project.

Is there a payment for participation?

No. There is no reimbursement for agreeing to take part in this study.

Who will know that my child has taken part?

The study will be confidential and a pseudo-name will be given to all children, for example student 1, student 2, etc. to ensure that no participant can be identified.

How will the information be used? Will the data collected be securely stored?

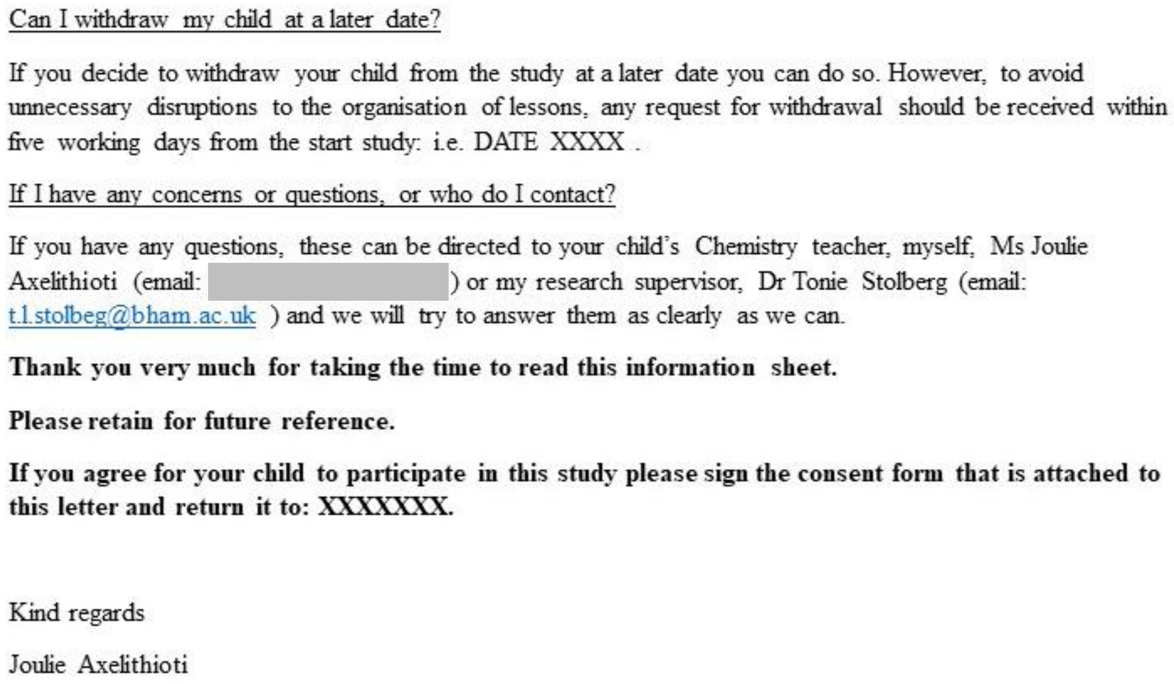
Lessons will be recorded by using school's equipment and only the school, the researcher and the researcher's supervisor will have access to these videos.

The data will be stored at the school according to school regulations and at the University of Birmingham for 10 years under the University's Code of Practice for Research.

What happens is I don't want my child to be part of this study?

If you do not want you child to be part of the study, then your child's participation in these classes will not be analysed.

Information sheet for parents and guardians of student participants, page 1



Can I withdraw my child at a later date?

If you decide to withdraw your child from the study at a later date you can do so. However, to avoid unnecessary disruptions to the organisation of lessons, any request for withdrawal should be received within five working days from the start study: i.e. DATE XXXX .

If I have any concerns or questions, or who do I contact?

If you have any questions, these can be directed to your child's Chemistry teacher, myself, Ms Joulie Axelithioti (email: [redacted]) or my research supervisor, Dr Tonie Stolberg (email: t.l.stolbeg@bham.ac.uk) and we will try to answer them as clearly as we can.

Thank you very much for taking the time to read this information sheet.

Please retain for future reference.

If you agree for your child to participate in this study please sign the consent form that is attached to this letter and return it to: XXXXXXXX.

Kind regards

Joulie Axelithioti

Information sheet for parents and guardians of student participants, page 2