



University
of Glasgow

Wang, Di (2026) *Developing students' critical thinking through the 7E inquiry-based learning model in STEAM education*. PhD thesis.

<https://theses.gla.ac.uk/85967/>

Copyright and moral rights for this work are retained by the author

A copy can be downloaded for personal non-commercial research or study, without prior permission or charge

This work cannot be reproduced or quoted extensively from without first obtaining permission from the author

The content must not be changed in any way or sold commercially in any format or medium without the formal permission of the author

When referring to this work, full bibliographic details including the author, title, awarding institution and date of the thesis must be given

Enlighten: Theses

<https://theses.gla.ac.uk/>
research-enlighten@glasgow.ac.uk



University
of Glasgow

PHD THESIS REPORT

**Developing Students' Critical Thinking through the 7E
Inquiry-Based Learning Model in STEAM Education.**

By

Di Wang

BSc, MA

Submitted in fulfilment of the requirements of the Degree of:

Doctor of Philosophy

School of Social and Environmental Sustainability

College of Social Sciences

University of Glasgow

September 2025

Table of Contents

Abstract	6
Acronyms and abbreviations used	7
List of Tables	8
List of Figures	10
Acknowledgement	12
Author’s declaration	15
1. Introduction	16
1.1. Research background	16
1.2. Research questions and aims	18
1.3. Significant of the study	18
1.4. Organisations of the thesis	19
2. Policy analysis on CT, IBL and STEM education in China	20
2.1. Aims of the policy analysis	20
2.2. STEM education policies in mainland China	21
2.3. STEM/STEAM education policies in Hong Kong	24
2.4. Policies on CT and IBL that influence the policy of STEM education in China	27
2.4.1 The core competencies and values for Chinese students’ development (CCVCSD)	27
2.4.2. The Outline of the 14th five-year plan (2021-2025) and the vision for 2035	30
2.4.3. Compulsory education curriculum reform (CECR)	31
2.5. Practice of STEM/STEAM education in schools	33
2.5.1. Shanghai case	33
2.5.2. Wider survey	34
2.6. Drivers of policy changes in implementing educational policies	36
2.7. The relationship between policy formulation and practical implementation	38
2.7.1. Strengths of STEM/STEAM education practices in mainland and Hong Kong	38
2.7.2. Three main challenges and barriers between policy and implementation	38
2.8. Summary and recommendations	40
3. Literature review	42
3.1. Introduction	42
3.2. Methodology for literature review	43
3.3. Theoretical foundations	45
3.3.1. Constructivist learning theory	45
3.3.2. The Learning cycle model	48
3.3.3. Inquiry-based learning.....	50
3.4. STEM education theories and pedagogical frameworks/models	52
3.4.1. In Western contexts.....	52

3.4.2. In Asian contexts	53
3.5. CT and IBL in STEM education contexts	54
3.5.1. The development of CT in STEM education	54
3.5.2. The use of IBL method in STEM education	54
3.5.3. The development of CT through IBL	57
3.6. Integrated 7E IBL model and theoretical framework.....	59
3.6.1. Linking the IBL method with the 7E LC model	59
3.6.2. The revised 7E IBL model in this project	60
3.6.3. Theoretical framework	64
3.7. Conclusion and research gap.....	65
4. Methodology, research methods and intervention plan.....	67
4.1. Educational experiments	67
4.2. ‘True’ experiment and quasi-experiment	68
4.3. Mixed methods research	70
4.4. Research methods	71
4.4.1. Methods in educational research	71
4.4.2. Selection of Research context: Hong Kong.....	73
4.4.3. Selection of tests	74
4.5. Intervention plan in participating school	77
4.5.1. Plan introduction	77
4.5.2. Timeline and operating process	79
4.6. Quantitative and qualitative data analysis.....	81
4.6.1. Data collected	81
4.6.2. Data cleaning process	82
4.6.3. Quantitative data analysis plan	85
4.6.4. Qualitative data analysis plan	86
4.7. Research trustworthiness and ethics	87
4.7.1. Trustworthiness.....	87
4.7.2. Research ethics	88
5. The implementation of the 7E IBL model in participant school.....	89
5.1. The first draft of the 7E IBL model	89
5.2. Challenges from implementation and adaptations needed.....	89
5.2.1. Elicit	90
5.2.2. Elaborate	91
5.2.3. Extension	92
5.2.4. Notebook as a learning journal	93
5.3. The final version of the 7E IBL model.....	94
5.3.1. Aims of the new framework	95
5.3.2. Differences between the 7E LC model, the IBL method and the 7E IBL model (the new model), and the differences after implementations in class.....	95
6. Findings from quantitative data analyses	98
6.1. Research question 1: changes in CT dispositions	98

6.1.1. Pre-test for experiment group VS control group	98
6.1.2. Comparison: CT dispositions pre-and-post test.....	100
6.1.3. Summary on the changes in students' CT dispositions	117
6.2. Research question 2: changes in CT skills	118
6.2.1. Pre-test for experiment group Vs control group	118
6.2.2. Comparison: CT skills pre-and-post test	120
6.2.3. Summary on the changes in students' CT skills	135
6.3. Research question 3: The correlation between CT skills and dispositions.....	136
7. Findings from qualitative data analyses: examining changes in students' CT in different dimensions.....	138
7.1. Students' questions during lessons.....	138
7.1.1. The numbers of questions	138
7.1.2. The content of the questions	140
7.2. Students' performance and classroom atmosphere.....	146
7.2.1. In discussion section	146
7.2.2. In the extension section.....	148
7.3. Students' mastery of subject knowledge	150
7.4. Notebook in the extension step	153
8. Discussion.....	158
8.1. Summary of findings from qualitative and quantitative analyses	158
8.1.1. The impact on CT disposition	159
8.1.2. The impact on CT skills	159
8.1.3. Correlation between CT skills and dispositions.....	160
8.2. Factors influencing students' CT changes through the 7E IBL model.....	160
8.2.1. Pedagogical link between the 7E IBL model and students' CT	161
8.2.2. Possible reasons and improvement strategies for the changes in CT skills	165
8.2.3. Underlying mechanisms and theoretical foundations of the 7E IBL model's impact on students' CT skills and dispositions	171
8.3. Other factors impacting students' CT in STEAM education	183
8.3.1. Feedback from participants teachers on the 7E IBL model.....	183
8.3.2. Teachers' enactment as a key role: their professional development and support	186
8.3.3. The role of learning journals and metacognitive reflection in cultivating CT	189
9. Conclusions	193
9.1. Introduction	193
9.2. Contribution to knowledge	193
9.3. Limitations	195
9.4. Future study	196
9.5. Implications.....	197
9.5.1. Theoretical implications.....	197
9.5.2. Practical implications	198
9.6. Overall.....	200

<i>References</i>	203
<i>Appendix</i>	213
Interviews Forms	213
Class Observation Form	214
Questionnaires for CT dispositions - Chinese version	217
Questionnaires for CT dispositions - English version	218
Teacher training workshop PowerPoint slides (part of) examples	219
Coding for interviews - examples	220
Notebook answers - examples	222
Students' products examples	225

Abstract

An intervention study was carried out using a researcher-developed 7E IBL (7E Inquiry-Based Learning) model within STEAM (science, technology, engineering, arts and mathematics) education lessons at a public secondary school in Hong Kong, involving 240 students aged 13–15 in early 2023. This project used a mixed methods to examine how the model influenced the development of students' CT (critical thinking). Quantitative analysis showed that the experimental group demonstrated a statistically significant improvement in CT dispositions, as measured by the California Critical Thinking Disposition Inventory – Chinese Version (CTDI-CV) ($p < 0.001$). While the overall CT skills scores, measured by the Educate Insight: K-12 School Assessment, did not show statistical significance ($p = 0.098$), the mean score increased from 85.96 (out of 100) to 87.31, suggesting an upward trend. The control group showed no meaningful change in either measure.

The qualitative findings aligned with the quantitative results, where participating teachers expressed positive views of the 7E IBL model. Findings from qualitative data suggest that the 7E IBL model increases students' CT by building a coherent base of knowledge, encouraging curiosity-driven enquiry, and embedding metacognitive activation and reflective feedback into the learning process. Metacognitive activation, CT engagement, and reflective feedback appeared to be particularly effective in fostering both metacognitive development and the expansion of subject-specific understanding. The active role of teachers, together with students' use of reflective notebooks, is also considered an important factor in this process.

Based on the above findings, this study also recommends that teachers receive appropriate preparation before implementing the new model, including a deep understanding of each stage and the confidence to apply it flexibly. In practice, carefully designed, context-rich inquiry tasks that combine individual initiative with structured collaboration are essential, as is guided reflection at the close of activities. Extending the implementation over two semesters or an entire school year may give students the time and experience needed to internalise CT habits more fully. Overall, this project established a new teaching model, the 7E IBL model, for STEAM education and provides empirical evidence for its use in secondary schools, offering practical guidance for future teaching innovations and research in this area.

Acronyms and abbreviations used

AI	Artificial Intelligence
CCTST-2000	California Critical Thinking Skills Test - 2000
CCVSD	The core Competencies and Values for Chinese Students' Development
CECR	Compulsory Education Curriculum Reform
CNKI	China National Knowledge Infrastructure
CT	Critical Thinking
CDI	Critique-Driven Inquiry
CSEDS	Chinese Society of Educational Development Strategy
EBL	Enquiry-Based Learning
EDB	Hong Kong Education Bureau
IBL	Inquiry-based Learning
ISC	Inquiry Social Complexity
LC	Learning Cycle
LCM	Learning Communities in Mathematics
NGSS	Science Education Standards States
PBL	Project-Based Learning
Problem-BL	Problem- Based Learning
SAR	Special Administrative Region
SS	Secondary School
SML	STEM Maker Lesson
STEM	Science, Technology, Engineering, Mathematics
STEAM	Science, Technology, Engineering, Arts, Mathematics
UNESCO	United Nations Educational, Scientific and Cultural Organisation
VR	Virtual Reality
3E	Engage, Explore, Explain
5E	Engage, Explore, Explain, Elaborate, Evaluate
7E LC Model	Elicit, Engage, Explore, Explain, Elaborate, Evaluate, Extend
7E IBL Model	Preparation, Design, Inquiry, Presentation, Extension

List of Tables

Table 1: Relevant STEM education policies in China	21
Table 2: Seven tasks in CSEDS (CSEDS, 2024)	23
Table 3: STEM/STEAM education policy in Hong Kong	24
Table 4: The Core Competencies and Values for Chinese Students' Development / The Core Literacies for Chinese Students' Development	28
Table 5: Databases searched for Literature Review	43
Table 6: Numbers of publications selected and retrieved in total	43
Table 7: Review of selected publications	44
Table 8: Number of publications in CNKI (China), BEI (UK) and ERIC (US) from 2010 to present.	45
Table 9: Key features of a quasi-experiment and their application in this study (Cohen et al., 2002)	69
Table 10: Definitions of each component of critical thinking skills (Facione, 1990).....	75
Table 11: The definitions of each component of critical thinking disposition (Facione, 1990; Peng et al., 2004)	75
Table 12: Four main types of multiple-choice tests	75
Table 13: Details of the experimental and control groups in participating school.	77
Table 14: The final plan: Timeline for pre-test and post-test in participating school.	77
Table 15: S2 STEAM education curriculum content in participant school	81
Table 16: S3 STEAM education curriculum content in participant school.	81
Table 17: Data collected from pre-test in participant school.	82
Table 18: Numbers of pre-test participants for each group.....	82
Table 19: Data cleaning rules for CT skills.....	83
Table 20: Final numbers of CT skills test	83
Table 21: Questionnaire pairing rules	Table 22: Final numbers of CT dispositions
dispositions	85
Table 23: The differences between 7E LC model, IBL method and the 7E IBL model	95
Table 24: Differences from PBL method that participant school used and the 7E IBL model.	96
Table 25: Group statistics for CT dispositions	98
Table 26: Experimental and control groups pre-test independent samples test	99
Table 27: Pre-test CT dispositions scores (include class 3E).....	100
Table 28: Post-test CT dispositions scores (include 3E class)	101
Table 29: Group statistics for experimental and control group (exclude 3E class).	101
Table 30: Experimental group independent sample test (exclude 3E class)	102
Table 31: Control group independent sample test (exclude 3E class)	103
Table 32: Independent samples effect sizes comparing post-test CT overall scores between experimental and control groups.....	105
Table 33: CT disposition 7 metrics group statistics (include 3E pre-test)	107
Table 34: Independent samples test for 7 metrics in CT dispositions (include 3E class)	110
Table 35: Difference in differences (DiD) of experimental and control groups	110
Table 36: Summary of changes in students' CT dispositions after intervention	117

Table 37: Group statistics for CT skills	118
Table 38: Experimental & control groups' pre-test independent samples test for CT skills..	118
Table 39: Group statistics for experimental and control group in CT skills	120
Table 40: Experimental group independent sample test	120
Table 41: Control group independent sample test.....	121
Table 42: ANOVA analysis for pre-test CT skills scores	123
Table 43: ANOVA analysis for post-test CT skills scores.....	123
Table 44: Independent samples test for 8 metrics in CT skills	126
Table 45: DiD of experimental and control groups.....	126
Table 46: Summary of changes in students' CT skills after intervention	135
Table 47: Descriptive statistics for CT skills and dispositions: S2+S3.....	136
Table 48: Correlations analysis between CT skills and dispositions	137
Table 49: Summary of changes in students' CT skills and dispositions after intervention....	158
Table 50: Linke between CT skills to the 7E IBL model with corresponding student tasks.	161
Table 51: Linke between CT skills to the 7E IBL model with how model influence students' CT dispositions.	163
Table 52: Different types of Socratic Questions and their examples (Paul & Elder, 2007)...	178
Table 53: Examples of Metacognitive and CT Prompts, and Corresponding CT Processes in STEAM Activities.....	182
Table 54: A multi-dimensional teachers professional development support system (Desimone, 2009; Garet et al., 2001)	188

List of Figures

Figure 1: Chapter 43 of the outline of the 14th five-year plan (2021-2025) and the vision for 2035.....	30
Figure 2: 3E, 5E and 7E LC models (Karplus & Thier, 1967; Bybee, 1990; Eisenkraft, 2003)	48
Figure 3: Inquiry-based Learning (Lembens and Abels, 2016) cited by (Hofer, et al., 2018).50	
Figure 4: Phases of IBL (Pedaste et.al., 2015).....	51
Figure 5: The link between IBL and 7E LC model.....	60
Figure 6: The first draft of the 7E IBL model according to 7E LC model and IBL	60
Figure 7: Theoretical framework of this study.....	64
Figure 8: Research gap addressed in this study	67
Figure 9: Distribution methods example for groups in CT skills	78
Figure 10: Timeline and instruction for the intervention plan	79
Figure 11: The process of thematic annuluses (Braun and Clarke, 2006; Maguire and Delahunt, 2017).....	87
Figure 12: The first draft of the 7E IBL model according to 7E LC model and IBL	89
Figure 13: The final version of the 7E IBL model.....	94
Figure 14: Frequency percent of experimental group in pre-test.....	99
Figure 15: Frequency percent of control group in pre-test	99
Figure 16: Distribution of the different scoring bands for CT dispositions.	100
Figure 17: Overall estimated marginal means (exclude 3E class).....	103
Figure 18: Estimated marginal means (include 3E class).....	104
Figure 19: Simple boxplot of CT dispositions Overall score in pre and post-test for experimental and control group.	104
Figure 20: 1. Truth seeking: estimated marginal means	111
Figure 21: 2. Open- mindedness: estimated marginal means	111
Figure 22: 3. Analyticity: estimated marginal means	112
Figure 23: 4. Systematicity: estimated marginal means	113
Figure 24: 5. Confidence in Reasoning: estimated marginal means	114
Figure 25: 6. Curiosity: estimated marginal means	115
Figure 26: 7. Cognitive Maturity: estimated marginal means	116
Figure 27: Frequency percent: experimental group pre-test in CT skills	118
Figure 28: Frequency percent: control group pre-test in CT skills	119
Figure 29: CT skills Overall scores: estimated marginal means.....	122
Figure 30: 1. Analysis: estimated marginal means	127
Figure 31: 2. Inference: estimated marginal means	128
Figure 32: 3. Evaluation: estimated marginal means.....	129
Figure 33: 4. Induction: estimated marginal means.....	130
Figure 34: 5. Deduction: estimated marginal means.....	131
Figure 35: 6. Interpretation: estimated marginal means	132
Figure 36: 7. Explanation: estimated marginal means.....	133
Figure 37: 8. Numeracy: estimated marginal means.....	134
Figure 38: Scatter plot, relationship between CT disposition (x-axis) and skills (y-axis).....	137

Figure 39: Scatter plot, relationship between CT disposition (y-axis) and skills (x-axis)..... 137

Acknowledgement

Four years have passed so quickly that I couldn't complete all the books I hold dear, nor to realise the many plans in life. Yet in another way, this same stretch of time felt profoundly slow, for it allowed my former self to grow from someone uncertain and confused into who I am today, filled with purpose and fortitude. I am grateful to my younger self for choosing to pursue a PhD, for that courage, and for never giving up along the way. But most of all, I want to thank those who accompanied me along this journey, offering their unconditional support: my beloved family, my supervisors that I deeply respect, Dr Shaista Shirazi and Professor David Lundie, and everyone who has provided support to me.

Dr. Shaista Shirazi has been not only my academic supervisor, but also a mentor in my life. Thank you, Tara, for the selfless guidance and genuine care you have provided throughout the past four years. Every bit of your patience and every word of thoughtful advice have profoundly nurtured my growth. Your genuine care and deep sense of responsibility towards your students embody what it truly means to be an educator. People often say that we meet many teachers in our lives, but finding a true mentor is a rare blessing. I count myself truly fortunate to have met such a mentor in you, and also in Professor David Lundie. David's role in my academic journey has been equally essential. Your rigorous approach to research and relentless pursuit of knowledge have deeply inspired me, and I am grateful for every patient guidance and warm encouragement you have offered. The influence both of my supervisors had on me during my early research years will stay with me for life.

Appreciate to all participants who contributed data to this thesis, including the school principal, teachers, and students. Particular thanks are extended to the school principal, whose support as an educator holding an Educational Doctorate was essential to the successful completion of this study and to my academic development. I also gratefully acknowledge the four participating teachers who, despite their demanding schedules, engaged fully with the project and demonstrated an open-minded attitude towards

I would like to express my sincere appreciation to the academic and administrative staff at the University of Glasgow for their support throughout my doctoral studies. In particular, I thank

Dr Saima Salehjee, my third supervisor in my second year, for her guidance and for the opportunity to serve as her teaching assistant, through which I developed greater independence as a higher education teacher. I am also grateful to Dr Michele Vincent, Dr Anna Beck, Dr Naomi Richards, Professor Patrizia Riganti and all the teachers I had the privilege to work with, as well as the administrative team for their patience with my many enquiries. My thanks further extend to my colleagues Yingying, Yuting, Dianyuan, Zhenxin, Hui and Keke for their generous hospitality and encouragement, and to Yangzi, Jinyu, Dr Jiren Xu, Mokter, Atiah, Mohammad, Ted and Sajeeb for the companionship and joy shared through many conversations and meals.

I would also like to express my sincere gratitude to Professor Xiaohui Chen and Dr Simiao Pan, both of whom have played significant roles in my academic journey. Professor Chen, my undergraduate supervisor, has supported and encouraged me since my early academic years, for which I am deeply appreciative. I am equally grateful to Dr Pan for her continued guidance, encouragement, and collegial support throughout my PhD journey, as a trusted companion in academia.

I am also grateful to those beyond academia who enriched my doctoral journey. I extend my sincere thanks to Auntie Meijuan and Uncle Alex for their constant care, prayers, and spiritual support throughout my studies. My heartfelt appreciation goes to Sonia, Vince, Auntie Grace, uncle, Popo, Caitlyn and Keira whose warm home became a place of rest and encouragement during many weekends. I am thankful to my friends in Manchester, including Chenchen, Dr Han, Charlotte, Thomas, Felix and Jimmy, and to my friends in London, Qixuan, Martin, Sonia, Min, Arthur, and Eric, whose friendships brought colour and vitality to my life. I also appreciate my church community for their prayers, and in particular Harmienke and Dr Emiel Jerphanion for their faithful spiritual guidance and generous hospitality throughout this journey. I also thank my fur friends Tinkie and Pixie for the many dog walks that brought simple joy.

Finally, I want to say that since childhood, my parents have been my role models in life. Your dedication to your respective fields, along with your commitment to lifelong learning, has profoundly shaped who I am. It is your unconditional love, unwavering support, and boundless trust that have given me the freedom and courage to always remain true to myself, a debt of

gratitude I can only hope to repay over a lifetime. I also thank my younger sister Xiaoxue, whose thoughtfulness and constant support with our parents have been my greatest reassurance while pursuing studies far from home. Knowing you are there, caring for everything in my absence, has allowed me to fully devote myself to my academic journey. You are my pride, and I wish you courage as you chase your own academic and professional dreams. Dr Michael Chu, no single title could fully capture your presence in my life: partner, beloved, soul anchor, navigator, and my biggest fan. Each role you embody has become indispensable to my world. Thank you for your steadfast companionship throughout my studies, for your patient listening and emotional comfort. In the journey ahead, I look forward to walking beside you, growing together, striving together, and cherishing every moment God blessed. I also want to thank my little boy, the cutest cat, Bubu Wang, for the companionship, comfort, and joy he has brought to me each day.

I want to praise God, He is the light, the only and loving shepherd of my life.

Following my Viva, I experienced a profound loss with the passing of my supervisor, Dr Shaista Shirazi. I extend my deepest condolences to her family. This PhD thesis is dedicated to her memory, in recognition of her guidance, support, and lasting influence on my academic journey. May she rest in peace.

Author's declaration

I declare that, except where explicit reference is made to the contribution of others, that this dissertation is the result of my own work and has not been submitted for any other degree at the University of Glasgow or any other institution.

Printed Name: _____ Di Wang _____

Signature:

1. Introduction

1.1. Research background

STEAM (science, technology, engineering, art and mathematics) education signifies an emerging interdisciplinary subject which strives to foster students' comprehensive understanding of scientific concepts. Since its inception, the subject has undergone the evolution of several variants, including STEM (where STEAM refers to 'STEM' plus the addition of the arts) and STEM+, which emphasises the interdisciplinary and multidimensional aspects of each subject. As Yakman (2006) explained, STEAM brings together different elements: maths is the foundation, science and technology are the tools, and arts and engineering help expand and apply what is learned. In this report, the term STEAM education will be used to refer to this integrated approach, including its related forms. Originating in the United States, STEAM education was initially introduced as a national policy spanning the primary, secondary, and higher education sectors (Pcast, 2010). Gradually, motivated by rapid scientific and technological developments, STEAM education has seen a global proliferation, expanding to reach other developed nations, such as the United Kingdom, Germany, France, Japan, and Singapore, as well as emerging economies, including China, Russia, and India. In current times, the popularity of high technology, such as AI (Artificial Intelligence), has led governments and educators to acknowledge the importance of prioritising STEAM education as a means of bolstering national competitiveness. STEAM education aims to equip students with practical competencies that contribute to cultivating an innovative new generation, one capable of responding to the growing global demand for 21st-century talent (Schweingruber et al., 2014). It could help students develop a set of higher-order thinking skills, such as creativity and CT, practical abilities like teamwork, problem-solving, and adaptability to deal with the fast changes and challenges of today's world (Schweingruber et al., 2014). Among the various skills that can be fostered through STEAM education, this study focuses on students' CT, not only because it is a fundamental cognitive ability but also due to its close relevance to inquiry-based learning activities often found in STEAM classrooms. CT has three mainstream definitions in various subjects, including education, philosophy, and the psychology field (Lai, 2011). In this project, the researcher will focus on the meaning of education. As Halpern (2014) highlighted, CT involves both cognitive skills and a set of goal-oriented problem-solving. In other words, CT is not only about analysing information or evaluating knowledge but also about making reasoned judgments, questioning assumptions, and approaching problems creatively and reflectively (Diane F Halpern, 2014).

STEAM education, closely tied to the rapid advancement of emerging technologies such as 3D printing, VR (Virtual Reality), and AI, has continued to receive growing attention over the past decade. The government has invested notably in the development of STEAM education in schools across both mainland China and Hong Kong, through funding and policy support. In particular, the Hong Kong EDB (Education Bureau) provides each secondary school with an annual allocation of dedicated resources to support the implementation and enhancement of STEAM education. Chapter 2, the Policy Analysis, will illustrate this in detail. However, in actual classroom practice, influenced by the traditional teaching way for few decades, many STEAM education lessons may still be akin to traditional teacher-centred approaches in China (Zhang & Hou, 2019). These often lack effective tools or standardised teaching models to support deep interdisciplinary integration, making it difficult to achieve the broader goals of STEAM education, which go beyond subject knowledge to include the development of diverse and transferable competencies (Thibaut et al., 2018). For example, in the participating school in this project, in many cases, course design remains focused on one-way knowledge delivery, so that students may participate in hands-on activities, they often follow step-by-step instructions given by the teacher, leaving limited space for independent inquiry, collaboration, or using CT. As a result, opportunities for meaningful, exploratory learning in real-world scenarios are limited. More commonly, STEAM lessons are "non-exam subjects," much like arts subjects. They often become "tech-based craft classes," where students use digital tools to complete preset tasks. Under such arrangements, the academic seriousness and cognitive depth of the course are weakened. In the meantime, students tend to view STEAM education as a break from formal learning rather than a structured process for building the necessary competencies. Consequently, it clearly diverges from the original aim of STEAM education, which is to promote integrated skill development and lifelong learning ability through hands-on, inquiry-based activities.

The causes of these problems are not only rooted in how current education systems undervalue non-exam subjects, but also in the lack of a structured, goal-oriented, and inquiry-driven teaching model that can be easily implemented and scaled. In response to this gap in both theory and practice, this study aims to develop a more systematic and pedagogically sound instructional model for STEAM education, referred to as the 7E IBL model. This model is designed to address structural challenges in classroom implementation, improve the overall quality of STEAM education teaching, and support students, especially in the development of

CT, within interdisciplinary learning environments. The following section introduces three research questions.

1.2. Research questions and aims

- **To what extent does an intervention that uses the 7E IBL model in STEAM education influence secondary students' CT dispositions?**
- **To what extent does an intervention that uses the 7E IBL model in STEAM education influence secondary students' CT skills?**
- **Is there a correlation between the impact of CT dispositions and skills?**

1.3. Significant of the study

This study offers theoretical value by proposing and testing a new instructional model, the 7E IBL model, that combines elements of the 7E LC (learning cycle) model with IBL (inquiry-based learning). Definitions of each theory will be introduced in chapter 3, Literature Review. This model takes a different approach from many existing frameworks. Whereas many traditional models tend to centre on a single subject or adopt a linear approach, the 7E IBL model, as an integrated model, encourages interdisciplinary learning and offers students structured support in developing CT. This study helps fill a gap in the existing literature by demonstrating how integrated models can be effectively applied in real classroom settings within STEAM education, thereby deepening our understanding of their potential in practice. The study also examines how each stage of the model supports the development of different aspects of students' CT. This helps to explain how CT emerges in STEAM education learning environments and offers a valuable starting point for future research in education and cognitive development, especially in the context of adolescent learners.

Regarding its practical significance, this study offers valuable guidance for STEAM teachers, particularly for young educators new to STEAM education. The 7E IBL model supports teachers in designing more engaging lessons that provide students with real opportunities to strengthen skills such as CT and problem-solving. It also offers curriculum developers and education organisations a practical base for building integrated STEAM programmes that respond to today's educational needs. In addition, this research gives policymakers evidence

that interdisciplinary and inquiry-based teaching can support higher-order thinking skills, offering a basis for more informed curriculum and policy decisions. At a broader societal level, the model's emphasis on student-led inquiry and reflection supports the growth of independent learners who are better prepared to handle complex challenges. By encouraging curiosity and fostering long-term engagement with knowledge, the 7E IBL model lays the groundwork for lifelong learning and innovation.

1.4. Organisations of the thesis

In the next stage of research, the study will begin with a policy analysis to examine how IBL, STEAM education, and CT are currently positioned and implemented within existing education policies in China. It aims to highlight, from a systemic perspective, the importance of cultivating CT and the growing urgency of promoting interdisciplinary learning in secondary schools. Following this, a literature review will be conducted through three key aspects: (1) CT in STEAM education; (2) the use of IBL methods in STEAM education; and (3) the development of CT through IBL. The review will not only summarise existing findings but also identify research gaps and limitations in the current body of work, offering a clear rationale for the originality of this study. Building on these foundations, the study will then detail the methodology and research methods, including the implementation process carried out in the participating school. A mixed-methods approach will be used to collect both quantitative and qualitative data, which will be systematically analysed to present key findings. Finally, the discussion chapter will explore the significance of the results, examine possible contributing factors, and consider their educational implications. The conclusion will summarise the main findings and offer recommendations and insights for future educational practice and policymaking.

2. Policy analysis on CT, IBL and STEM education in China.

2.1. Aims of the policy analysis

Policy analysis can help readers understand the background and necessity of STEM education development across various countries and regions systematically, from a national decision-making perspective. By examining empirical gaps between policy design and classroom implementation, researchers can prevent their work from becoming overly idealistic, thereby fostering research with greater real-world impact (Tseng, 2012). Research should not only describe policy phenomena but also help policymakers and practitioners identify actionable and impactful directions, thereby enabling the development of feasible recommendations for practice and reform (Tseng, 2012). Moreover, this approach aims to closely connect this project with national education plans, bridging educational needs while elevating the practical relevance and applied value of the research. Thus, this chapter will analyse policies concerning STEM education and IBL activities, alongside guidelines for cultivating CT. This analysis will substantiate the necessity of this research and remind scholars to pursue implementable projects offering practical reference value for educators. The policy analysis will be conducted from the following questions:

- What are the STME education policies in Mainland China and Hong Kong?
- What are the policies on CT and IBL that related to STEM education in China?
- How do policies on STEM education impact its practice in China?
- What is the relationship between policy formulation and its practical implementation in China?
- What are the reasons for changes that have influenced the policies from the perspective of the practice?

2.2. STEM education policies in mainland China

Time	Policy	Short summary and meaning in STEM/STEA education
2006	National Medium-and-Long-Term Program for Scientific and Technological Development (2006-2020)	To advocate the design of heuristic teaching methods to augment students' scientific and technological literacy
2015	Thirteenth Five-Year Plan for Education Informatisation (Draft for Comments)	It delineated the imperative of exploring novel educational paradigms, notably STEM education and creator education.
2016	Thirteenth Five-Year Plan for Education Informatisation	It was imperative trend for China to cultivate STEM education programs, thereby equipping students with the knowledge and skills demanded on a global scale
2017	China STEM Education White Paper	There is a notable progression towards the sector's maturity and professionalisation of STEM education.
2021	The outline of the 14th Five-Year Plan (2021-2025) and the Vision for 2035	China aims to elevate its education system to a high-quality standard, thereby paving the way for integrating STEM education into the Compulsory Education Curriculum Reform.
2022	Compulsory Education Curriculum Reform	Explicitly underscores the robust governmental support for implementing interdisciplinary curricula, including STEM educational activities or subjects, within schools.
2023	UNESCO's International STEM Education Research Centre established in Shanghai	It's a significant milestone for China's advancement in STEM education. The centre aims to explore universal accessibility for STEM through collaborative efforts.
2024	STEM Education 2035 Plan, Chinese Society of Educational Development Strategy, CSEDS	By 2035, the goal is to establish a high-quality STEM education system with Chinese characteristics, strengthening the training mechanism, evaluation system, and teacher development, while advancing international cooperation to build a strong education nation.

Table 1: Relevant STEM education policies in China

As shown in Table 1, although STEM education was not formally added to China's national policy document in 2006, STEM education appeared in the national development outline (Wang, 2017). In later policy documents, it is seen that Chinese STEM education was influenced by it in 2008 (Wang, 2017). The US NGSS (Science Education Standards States) (2013) claims that 'the goal of the U.S.' education is to develop a high science and technology base with solid science foundation skills. More specifically, science and technology foundation skills include basic academic knowledge and the ability to develop self-learning, investigate problem-solving skills, and think critically. The development of these skills is a core component of the STEM curriculum (NGSS, 2013). Influenced by the US policy and the rapid development of technology needs, in the 2016 policy 'National Medium-and-Long-Term Program from Scientific and Technology Development (2006-2020)', it was proposed that heuristic teaching methods should be designed to enhance students' science and technology literacies. Furthermore, these methods should highlight students' practical skills, independent thinking abilities, innovation, CT skills and the drive to acquire new knowledge. The Ministry of Education (2015) in China officially stated in its notice on the 'Thirteenth Five-Year Plan for Education Informatisation (Draft for Comments)' that it is essential "to explore new education models such as STEM education and creator education". Moreover, in (2016c), the 'Thirteenth Five-Year Plan for Education Informatisation' was released which clearly stated that China must develop STEM education courses to prepare students' knowledge of being a talent for global demand.

Following the above documents, in June 2017, the First China STEM Education Development Conference was held in Chengdu, jointly organised by the China Education Sciences Academy and the University of Electronic Science and Technology of China, among others. This conference marked the launch of the *2017 China STEM Education White Paper* and is widely regarded as a milestone in China's STEM education development. There were approximately 1000 people from various regions and fields attended the conference, including experts in education such as leaders from the Ministry of Education, principals, teachers, and representatives from education companies. After providing a summary and analysis of the current situation of STEM education in China, the conference formed a new direction for the development of STEM education. Following this meeting, the 'China STEM Education White Paper' (2017) was produced, which alluded to STEM education becoming more mature and professional within the sector. This document also shared the background of the development

of STEM education and summarised the difficulties and challenges encountered in practical terms from an international perspective (Sciences., 2017). Arguably the most crucial presentation during this conference was the 'China STEM Education 2029 Innovation Action Plan' (2017) (It is also a chapter in the White Paper), whereby the scholars associated with the display indicated the direction of STEM education over the next ten years and shared an outlook for its popularity. This undoubtedly set a strong precedent and confidence for scholars and educators at their initial stages of STEM education by showing that the field can be developed in China as a lifelong learning opportunity for all students as it is appropriate to the national context. Thus, STEM education research became a national need in China.

In 2023, The inauguration of the International STEM Education Research Centre by UNESCO (United Nations Educational, Scientific and Cultural Organisation) in Shanghai, represents a significant milestone for China's advancement in STEM education, solidifying its position as a pivotal global development focal point. This initiative seeks to foster collaborative efforts aimed at investigating how STEM education can be universally accessible in an AI-driven society. One year later, the Chinese Society of Educational Development Strategy (CSEDS) drafted the *China STEM Education 2035 Action Plan* (CSEDS, 2024). This plan outlined the goals and action guidelines for STEM education in China over the following decade, detailing seven specific tasks (see details in Table 2 below) along with corresponding measures. By 2035, the 10-year goal is to establish a high-quality STEM education system with Chinese characteristics, strengthening the training mechanism, evaluation system, and teacher development, while advancing international cooperation to build a strong education nation (CSEDS, 2024).

No.	Specific Goal
1	Build a STEM education research and practice system suited to China's national context
2	Explore integrated talent cultivation mechanisms for STEM (including approaches to education, school models, management systems, and support mechanisms)
3	Develop high-quality STEM education resources
4	Establish a STEM education evaluation system
5	Establish a STEM teacher training and professional development system
6	Promote the digitalisation of STEM education
7	Improve the collaborative mechanisms for STEM education

Table 2: Seven tasks in CSEDS (CSEDS, 2024)

2.3. STEM/STEAM education policies in Hong Kong

Time	Policy	Short summary and meaning in STEM/STEAM education
2015	Chief Executive's 2015 Policy Address issued by the Hong Kong Education Bureau (EDB)	STEM education has officially become a key development subject strongly supported by the Hong Kong Government, and nearly HK\$100 million (£10 million) has been allocated to support it.
2015	The "Promoting STEM Education-Report on Unleashing Creative Potential," released by the Hong Kong Education Bureau	Marking the official launch of the STEM education promotion programme in Hong Kong
2017	Chief Executive's 2017 Policy Address	The Education Bureau should increase its efforts to provide more resources for school-based courses such as STEM education to support their development
2022	Chief Executive's 2022 Policy Address	Vigorously promote the popularisation of STEAM education in all primary and secondary schools (public/government schools) in Hong Kong.
2023	Chief Executive's 2023 Policy Address	Aim to fully implement STEAM education subjects in the primary school curriculum by the 2025/26 academic year, and the secondary school STEAM education curriculum is being updated to ensure a smooth transition
2024	Chief Executive's 2024 Policy Address	Reaffirmed the EDB's commitment to STEAM education by promoting AI integration, strengthening digital strategy, and advancing both local and international academic exchange.

Table 3: STEM/STEAM education policy in Hong Kong

The overall implementation direction of STEM education in Mainland China and Hong Kong shares numerous similarities, primarily revolving around collaboration among local governments, education bureaus, and schools to foster the teaching of STEM subjects in primary and secondary education settings. However, as illustrated in Table 3, Hong Kong has tailored its approach by augmenting the dissemination of several policies contextualised within the local educational landscape and complementing China's overarching policies. In 2015, the Policy Address issued by the Hong Kong Education Bureau (EDB) particularly underscored the importance of advancing STEM education (EDB, 2015a). It delineated the developmental trajectory of STEM education disciplines (includes secondary schools) in Hong Kong for the subsequent decade (2015-2025) (EDB, 2015a). Towards the end of the same year, the "Promoting STEM Education-Report on Unleashing Creative Potential," released by the EDB (2015b), heralded the official commencement of this initiative in Hong Kong. In the 2017 Policy Address, EDB allocated STEM education development grants to every public/government primary and secondary school in the 2015/16 and 2016/17 academic years: HK\$100,000 (£10,000) for each primary school and HK\$200,000 (£20,000) for each secondary school. At the same time, the EDB strengthened teacher training by establishing a dedicated STEM Education Centre at the Arts and Technology Education Centre in Kowloon, which provided professional training and teaching support for all primary and secondary school teachers. With sufficient financial investment and a comprehensive teacher training system, these measures underscored the EDB's strong commitment to advancing STEM education in Hong Kong.

Similarly, the "Chief Executive's 2022 Policy Address" was unveiled in 2022, reaffirming the imperative to propagate engaging and diversified STEAM (adding 'Arts' component into STEM) education across Hong Kong, to nurture talent for the region's future development and innovation (EDB, 2022). In essence, to advance STEAM education, the EDB adopts a comprehensive and holistic approach, employing a spectrum of strategies concurrently. The overarching goal is to enhance students' aptitude for integrating and applying knowledge and skills across various disciplines, thereby unlocking their innovative potential and fostering their development into well-rounded individuals (EDB, 2022). The six STEAM education development strategies outlined by the Hong Kong EDB are as follow:

1. **Updating the curriculum for STEAM education**, ensuring that content remains relevant and aligned with emerging disciplinary and societal needs.
2. **Enhancing and diversifying student learning activities**, providing learners with more engaging and varied opportunities to apply knowledge.
3. **Facilitating access to learning opportunities and teaching resources**, thereby reducing barriers to participation and ensuring equity.
4. **Bolstering the professional development of schools and teachers**, with a focus on capacity building and sustainable growth.
5. **Cultivating partnerships with community stakeholders**, including industry and non-governmental organisations, to strengthen real-world connections.
6. **Evaluating and disseminating exemplary practices**, promoting the sharing of successful models to improve system-wide quality.

One year later, the EDB announced in the "2023 Policy Address" its aim to fully implement STEAM education subjects in the primary school curriculum by the 2025/26 academic year (EDB, 2023). Supporting initiatives such as teacher training are currently underway, and the secondary school STEAM curriculum is being updated to ensure a smooth transition for students moving from primary to secondary education (EDB, 2023). It is worth noting that, in the "2024 Policy Address," the promotion of STEAM education continued to feature in development plans, with proposals to integrate AI technology into teaching support (EDB, 2024). The government's sustained efforts include establishing a Digital Education Strategy Development Steering Committee, vigorously encouraging academic exchanges with mainland China and international innovation institutions and organising large-scale international education summits and teacher workshops to enhance the quality of digital/technology education (EDB, 2024). By adhering to these strategies, Hong Kong endeavours to strengthen its STEAM education framework and cultivate a proficient and innovative workforce poised to navigate the challenges of the future, with adequate financial backing and complementary teacher training.

2.4. Policies on CT and IBL that influence the policy of STEM education in China

In the first two sections, the three latest policies will be introduced: 1. The core Competencies and Values for Chinese Students' Development (CCVSD) (2016a); 2. The Outline of China the 14th Five Year Plan (2021-2025) and the Vision for 2035 (2021); 3. Compulsory Education Curriculum Reform (CECR) (2022). The first and second policies serve as the background for the third one.

2.4.1 The core competencies and values for Chinese students' development (CCVCSD)

During the Third Plenary Session of the 18th Central Committee of the Communist Party of China, the full context of the Core Competencies and Values for Chinese Students' Development (CCVCSD) (2016b), also known as the Core Literacies for Chinese Students' Development, was emphasised by the Chinese Ministry of Education. The CCVCSD summarises the characteristics and adaptations that are essential for a Chinese student to acquire during their compulsory study stages (including primary and secondary schooling). The main objective of these competencies and values is to cultivate the development of students' talents to meet the needs of a rapidly developing economic society. This will enhance the country's ability to compete in the international arena in the 21st century.

The CCVCSD contains three aspects and six main literacies, as shown in Table 4. Three of the six literacies involve the essential need for the development of CT and the use of an inquiry approach in learning. The literacies include scientific spirit, learning how to study, and innovation in practice, and there are three essential elements within each.

Aspects	Main Literacies	Essential Elements
Cultural Foundations	Cultural Heritage	Humanities Accumulation
		Humanistic Feelings
		Aesthetic Sensibility
	Scientific Spirit	Rational Thinking
		Critical Thinking Skills
		Inquiry with Courage
Self-Developments	Learning How to Study	Enjoying and Excelling at Study
		Diligence in Reflection
		Information Awareness
	Healthy Lifestyle	Cherish Lives
		Healthy and Comprehensive Personality
		Self-Management
Social Engagement	Responsibility	Social Responsibility
		National Recognition
		International Understanding
	Innovation in practice	Labour Awareness
		Problem Solving
		Use of Technology

Table 4: The Core Competencies and Values for Chinese Students' Development / The Core Literacies for Chinese Students' Development

The three essential elements of scientific spirit literacy are rational thinking, CT, and inquiry with courage. These CT skills require students to utilise their individual abilities to question and evaluate their knowledge in a more comprehensive manner. First, scientific spirit literacy encourages learners to adopt a bold and positive attitude when using CT skills to solve problems effectively during IBL. Scientific spirit literacy involves the development of students' value criteria, the way they think, and their ability to express themselves (China., 2016b). It is built through inquiry-based learning, where students can understand scientific knowledge and skills in a way that enables them to demonstrate complete comprehension. The CCVCSD (2016b) employs the same definition of "CT" in education as Western literature, which suggests that when making a decision or choice, evidence should be consulted to facilitate an analysis of different perspectives (Zhuo, 2019). The concept of inquiry with courage conveys that learners who possess curiosity and imagination also have the ability to persevere in inquiry and exploration without being held back by fear of difficulties.

Second, students' keen interest and appreciation, as well as their diligence in reflection and information awareness, are increased when they are introduced to effective learning study methods (2016b). Students must have positive attitudes, keen interest, appreciation for the value of education, knowledge of appropriate learning methods, and independent learning ability if they are to enjoy and excel at their studies. The main requirement for diligence in reflection is to review learning to gain experience continuously. This experience provides practitioners with the opportunity to choose or adjust learning strategies according to their context. Information awareness requires students to gain, evaluate, identify, and use the information independently and effectively. It is also essential for students to become comfortable with the developing trend of social informatisation by adopting essential digital technologies, abiding by cyber ethics, and practising information awareness.

Third, innovation in practice literacy elaborates upon students' practical abilities, consciousness, and performance of behaviours. Included elements are labour awareness, problem-solving skills, and the ability to use technology effectively (2016b). Regarding problem-solving skills, students are expected to find solutions to questions that arise during their individual studies. By increasing their CT abilities, students become able to independently identify solutions to new problems as they develop (Selwyn & Facer, 2013). The ability to use

technology effectively involves having an engineering literacy to transfer ideas and creativity into a tangible objective or improve and optimise existing items.

2.4.2. The Outline of the 14th five-year plan (2021-2025) and the vision for 2035

The outline of the 14th Five Year Plan (2021-2025) and the Vision for 2035 (2021) regarding national economic and social development were adopted at the Fourth Session of the Thirteenth National People's Congress in Beijing. They emphasise the goal of building a high-level education system which involves continue the deeper educational reform. The outline has 19 parts and 65 chapters; part 13 emphasises the goal of increasing the courtesy of citizens and promotion of their well-rounded development. Within part 13, chapter 43 highlights the priority of building a high-quality education system which will foster a generation that has a high-level literacy and practical abilities. Additionally, focus should be placed on developing students' morals, intelligence, athletic abilities, aesthetics, and citizenship skills. Consequently, there are five aspects within the chapter 43 concept, as shown in Figure 1. The aspect involving the promotion of equality in public education, is further divided into five main factors: a) Promote the equalisation of public education by facilitating the building of school facilities and teacher training, so that children in impoverished areas can enjoy the same level of learning as those in the more affluent cities. b) Ensure that all students have access to secondary education and encourage schools to diversify learning opportunities for students. c) Regulate after-school classes. d) Enhance accessible pre-school education and special education. e) The fifth aspect, in-depth educational reform, illustrates the need for upgrades within education evaluation systems and the cultivation of patriotism, spirit of innovation, citizenship education, and healthy personalities among students. It led to the reform of the compulsory education curriculum, including public primary and secondary schools, which will be introduced in the following section.

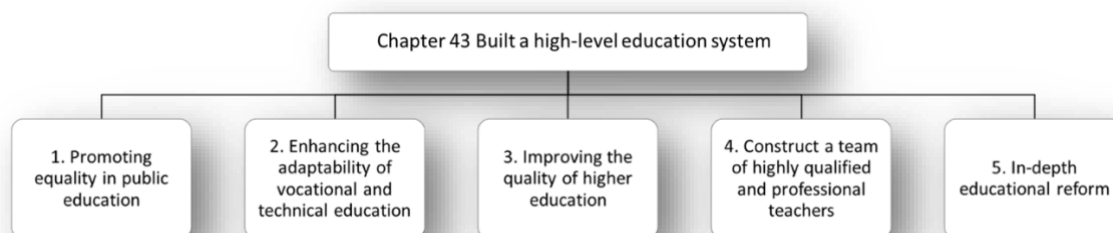


Figure 1: Chapter 43 of the outline of the 14th five-year plan (2021-2025) and the vision for 2035

2.4.3. Compulsory education curriculum reform (CECR)

According to the outline of the 14th Five-Year Plan, the Vision for 2035, and the CCVCSD, the Ministry of Education in China released the CECR (2022). It aims to construct an international standard education curriculum. Students are entitled to a guaranteed nine-year free education, known as Nine-Year Compulsory Education, as a result of a national policy funded by the Chinese government. This opportunity applies to all citizens in both primary and secondary schools. The compulsory education curriculum defines the educational objectives, content, and basic requirements for teaching. The Ministry of Education promulgated the first and second versions of the Compulsory Education Curriculum Development Programme in 2001 and 2011. Both the original and updated versions lead to improvements in teaching and learning, ensuring that the same basic educational opportunities are available to every child (PRC, 2022 CECR).

The latest vision of the CECR (2022), clearly defines how all students should be taught, what and for whom they should be educated. Due to rapid economic and technological development, the emphasis on educational accessibility has shifted to the need for a high-standard system of education. The following questions are answered in the CECR (2022).

What characteristic should a student develop as a product of education?

The latest version of CECR gives three main educational goals based on the CCVCSD. First, it should develop a generation that has a clear purpose and desire to pursue a well-rounded life. Second, it requires that an inquiry-based learning environment be provided, allowing students to develop CT and creative abilities. As suggested by studies, learning in a collaborative environment leads to the cultivation of communication and teamwork skills. Third, it asks students to become citizens who take full responsibility for themselves, society, and the world as a whole. A person who fits these criteria would understand the meaning of not only self-confidence, self-improvement, and solidarity, but also citizenship, cherishing lives, love, peace, and respect for other cultures (PRC, 2022 CECR).

How should students be taught?

There are five basic principles regarding how students should be taught, two of which highlight the importance of implementing inquiry-based learning methods into interdisciplinary study. As a result, the CECR (2022) was revised to allow for interdisciplinary study activities and to optimise the methods and strategies so that practical skills can be integrated and implemented. Inquiry-based learning, when paired with the use of CT, can help students develop their scientific spirit literacy, which includes gaining practical abilities. New curriculum requirements, strengthening an integrated curriculum and reinforcing students' varying skills and abilities, can therefore be achieved within the teaching process (PRC, 2022 CECR). Therefore, embedding inquiry-based learning within a STEM curriculum is the logical answer to the education of the next generation.

For whom should students be educated?

On the one hand, it is for students themselves, as they can be educated to cultivate their own well-rounded development. On the other hand, it is for the national needs of talent, which is to build a foundation of 21st-century talents for China, so that it can be rejuvenated as a powerful nation with socialist modernisation (PRC, 2022 CECR).

In conclusion, the latest education policies in China indicate that, based on CCVCSD standards, students have to develop CT to succeed in the 21st century. Additionally, based on the outline of the 14th Five-Year Plan and the Vision for 2035, a high-level educational system must be established, and further in-depth education reform must be implemented. Finally, based on the new five-year plan and the 2035 vision, the CECR of 2022 was developed to provide solutions for fostering talent by utilising the CCVCSD and establishing a comprehensive, standardised education system. One of the main goals of CECR is to use practical activities and inquiry-based learning methods to develop students' CT and creative abilities. CECR also requires schools to strengthen the connections between various disciplines by creating interdisciplinary study activities and opportunities, with the goal of developing students' 21st-century skills and talents and fulfilling the nation's needs. In brief, from the policy perspective, it shows that the growth and development of CT is necessary for the future of Chinese students. In addition, interdisciplinary and IBL activities, including STEM education, is crucial for the development

of the high-quality Chinese education system. Thus, China places great value on the use of STEM education and to grow students' CT, making this research useful and meaningful.

2.5. Practice of STEM/STEAM education in schools

2.5.1. Shanghai case

Aligned to the China STEM Education White Paper, Guan and Cai (2018) surveyed the implementation of STEM education in 26 primary and secondary schools in Shanghai. The findings revealed several challenges and patterns in the development of STEM education. In terms of facilities, fewer than half (46%) of the schools (a total of 26 participating schools) had dedicated classrooms and equipment for STEM education (Guan & Cai, 2018). In comparison, 27% of schools used science laboratories, while the remaining seven schools relied on ordinary classrooms. Regarding teaching staff, 20 schools employed their own teachers to deliver STEM education, 2 invited instructors from external educational organisations such as higher education and training institutions, and 4 adopted a mixed approach. With respect to curriculum design, 15 schools (nearly 60%) offered STEM as a separate subject through extended courses, 7 integrated it into science lessons via inquiry-based activities, and 4 adopted diverse teaching activities (Guan & Cai, 2018). Most schools scheduled STEM as a stand-alone subject for two consecutive 45-minute periods each week, while some split the sessions between STEM and science. It is worth noting that the time devoted to STEM education was much less compared to other subjects, accounting for only 6% of the total curriculum, whereas Chinese language accounted for 22%, mathematics for 20%, and English for 20% (Guan & Cai, 2018).

These data collectively indicate that STEM education is gradually being introduced into Chinese primary and secondary school classrooms, signalling the initial acceptance of educational modernisation and interdisciplinary teaching concepts. However, whether in terms of hardware investment, teacher development, curriculum development, or class time guarantee, it is still in the initial exploratory stage. It has yet to form a systematic and regular implementation system. To achieve the leap from "existence" to "excellence" in STEM education, more efforts are still needed in terms of policy support, resource allocation, and teacher professional development.

2.5.2. Wider survey

At the 2019 Third National STEM Education Development Conference, the Chinese Academy of Educational Sciences released an extensive survey of schools across eight regions, including North China, Northeast, East, South, Central, Southwest, Northwest, Hong Kong, and Macao. The study collected nearly 50,000 valid questionnaires from school leaders, teachers, and students (CECR, 2019). The findings highlighted that STEM education has been widely accepted and integrated into teaching practices in schools. Most school leaders and teachers acknowledged the importance of STEM for students' holistic development, indicating that policy implementation successfully attracted attention at the outset. In practice, STEM has taken two main forms: embedding activities within science-based courses or offering it as a separate subject. Consistent with CECR's later recommendation, most public schools in mainland China implemented STEM through thematic activities, while some private schools in developed cities such as Shanghai, Beijing, and Shenzhen offered it as an elective subject (CECR, 2019). In Hong Kong, policies since 2015 have emphasised making STEM education accessible to all public schools through curriculum inclusion, teacher support, and resource funding, resulting in a higher level of accessibility (EDB, 2022).

Students also expressed strong interest in STEM education (CECR, 2019). Despite this positive feedback, teacher training remained limited (CECR, 2019). Between 2017 and 2019, only 15% of teachers in eastern regions, 8% in central, and 13% in western areas had received STEM-related training, mainly through workshops (48%) and off-campus programmes (CECR, 2019). In contrast, Hong Kong offered more frequent and diverse training opportunities, such as the Education University of Hong Kong's STEM Professional Development Programme, funded by the Education Development Fund. The dissemination of STEM and the expansion of teaching resources were also constrained. Over half of school leaders reported no government funding for STEM, half of schools lacked STEM laboratories, and 83% suffered from inadequate investment in tools and equipment (CECR, 2019). In Hong Kong, the EDB provides substantial annual grants as well as up to HK\$1,000,000 through the "IT Innovation Lab in Secondary Schools" scheme (EDB, 2022). Major challenges in promoting STEM included shortages of qualified teachers (65%), limited curriculum resources (61%), insufficient funding (60.5%), and outdated infrastructure (44.7%), with nearly 70% of schools lacking teaching materials altogether (CECR, 2019). According to the data presented above, the following section discusses the key themes that emerge from the findings from different dimensions.

- *Teacher development*

Although STEM education has gained widespread acceptance and students exhibit a strong enthusiasm for learning, teacher training remains insufficient. Many regions lack systematic programmes for developing professional educators, resulting in a shortage of qualified teachers who can effectively deliver STEM content. This gap hinders the consistent implementation of STEM initiatives across different areas.

- *Funding and resources*

A persistent imbalance in resource allocation further constrains the growth of STEM education. Most schools in mainland China still struggle with limited funding, outdated facilities, and inadequate teaching materials. In contrast, the Hong Kong SAR has adopted a more systematic, high-investment approach, highlighting the disparity in financial commitment and infrastructure support between regions.

- *Curriculum and systemic support*

These discrepancies reveal the absence of a sustainable support structure for STEM education in mainland China. Without coherent policy guidance and long-term financial assurances, schools often rely on fragmented efforts rather than coordinated reform. This weakens the overall effectiveness of STEM implementation and prevents consistent progress nationwide.

- *Inequality and future implications*

Unless substantial improvements are made to mechanisms for resource provision, teacher professional development, and curriculum standardisation, STEM education may unintentionally intensify existing educational inequalities. The growing divide between public and private schools, and between developed and underdeveloped regions, risks widening further if these systemic challenges remain unaddressed.

2.6. Drivers of policy changes in implementing educational policies

Considering the evolution of STEM education and practice in China, although implementation has encountered considerable practical difficulties, the benefits lie in how educational practice demands have directly driven policy adjustments and optimisation. Examples include the continuous refinement of teacher training, the allocation of funding, and the establishment of various STEM education centres. Practical investigations have shown that the majority of teachers and school leaders in China recognise the importance of interdisciplinary education (CECR, 2019). Despite the progress, challenges remain, including inadequate facilities, limited curriculum time, and shortages of teaching resources, particularly in regions of mainland China where educational provision is less developed. Under these circumstances, a notable milestone was reached with the inaugural STEM Education Conference in Chengdu, held in conjunction with the release of the STEM Education White Paper (2017). The event marked an initial shift towards addressing teaching requirements, as the conference reviewed the status and challenges of STEM education, while the white paper outlined its intended developmental directions.

To meet urgent demands, China's CECR (2022) included interdisciplinary education, funding, teacher training programs, and additional resources. Jiangsu and Guangzhou, for instance, experimented with interdisciplinary project-based learning and school-based learning, giving teachers the chance to modify their methods and gain practical experience. In 2023, UNESCO established the International Institute for STEM Education in Shanghai, marking another achievement. Through cooperative research, policy discussions, curriculum development, and teacher training, it emphasises how China is now going beyond internal reform to play a more significant role in influencing STEM education around the world. The CECR (2022), in its pursuit of establishing a high-quality education system, indirectly spurred the formulation of the STEM Education 2035 Action Plan (2024). This plan explicitly mandates the development of teacher training, curricula, and assessment systems for interdisciplinary education such as STEM, promotes the creation of high-quality educational resources, and emphasises the integration of digital education with international collaboration. In other words, challenges encountered in practice continually inform policymaking, while new policy frameworks provide more substantial support for teacher development and curriculum reform. These practical difficulties compelled policy to evolve from conceptual advocacy towards institutionalised support for teaching needs and international communications.

Similarly, Hong Kong's STEM education policy undergoes continual development and adjustment in response to its implementation processes, in order to more effectively support policy enactment. In 2017, the EDB allocated special grants to public primary and secondary schools to improve STEM laboratories and teaching tools, directly addressing schools' pressing resource needs. From 2022 onwards, in response to rapid advances in technology and innovation, STEM was upgraded to STEAM (a trend also seen in some schools on the mainland) (EDB, 2022). The Policy Address (2024) further proposed integrating artificial intelligence into teaching support, establishing a Digital Education Strategy Development Steering Committee, and promoting innovative teaching through large-scale education summits and teacher workshops. In recent years, teacher training and research projects have also expanded. For example, the "STEAM Coordinator Workshops" provide teachers with professional development opportunities in interdisciplinary curriculum design, integration of digital tools, and engineering practice (EDB, 2024). At the curriculum level, primary science and junior secondary science courses have incorporated STEAM learning units, primary mathematics has piloted mathematical modelling, and AI and programming modules have been added at different stages of schooling (EDB, 2023, 2024). In addition, the EDB has funded schools and organisations to carry out STEAM-related research projects and curriculum experiments, demonstrating that policy initiatives go beyond slogans by linking teacher development, curriculum innovation, and research support to ensure practical implementation (2022, 2023, 2024).

Overall, the evolution of China's STEM education policy reflects a cyclical logic of "practice feedback, policy response, and practice validation." Classroom realities such as shortages of teachers and resources, limits imposed by examination systems, and the challenge of sustaining student interest have pushed policymakers to introduce more practical and actionable measures. For example, in its 2023 Policy Address, the Hong Kong EDB acknowledged the challenges in teacher resources identified in previous practice and set a goal to establish a Digital Education Strategy Development Steering Committee by 2025 to support the training of STEM teachers. At the same time, national strategies and international collaborations have provided new goals and resources to support progress. From the Chengdu conference and the release of the *STEM Education White Paper* to the *STEM Education 2035 Action Plan* and the establishment of international research institutes, and further to Hong Kong's financial investments, curriculum reforms, and teacher training initiatives, the trajectory of STEM/STEAM policy development

demonstrates that change has not been driven solely from the top down. Instead, it has evolved through the continuous interaction between practice and policy, with each stage informing and refining the next, as reflected in the annual updates to Hong Kong's Policy Address shown above in Table 3: STEM/STEAM education policy in Hong Kong. This dynamic offers valuable insight for designing more adaptive policies in the future.

2.7. The relationship between policy formulation and practical implementation

2.7.1. Strengths of STEM/STEAM education practices in mainland and Hong Kong

Overall, compared with Hong Kong, students in mainland China showed greater interest in participating in science classes and technology competitions, and parents expressed stronger support for STEM education at all school levels (CECR, 2019). However, during the three years from 2017 to 2019, schools in Hong Kong organised STEM-related courses and activities far more frequently than their mainland counterparts. In fact, training opportunities in Hong Kong were estimated to be about five times higher than those available in mainland schools (EDB, 2020). In terms of curriculum provision, the widespread adoption of STEM education in mainland China has largely been confined to primary schools, while at the secondary level it has mostly been limited to private schools in developed cities such as Beijing, Shanghai, Guangzhou, and Shenzhen, with very few public schools involved. By contrast, more than 60% of Hong Kong's 209 primary schools have introduced STEM education in some form, and in recent years an increasing number of secondary schools have also begun to establish STEM as a stand-alone subject (CECR, 2019). In short, while mainland students and parents tend to show higher levels of enthusiasm, Hong Kong schools have achieved far greater coverage of STEM education at both the primary and secondary levels.

2.7.2. Three main challenges and barriers between policy and implementation

The researcher concludes three main challenges and barriers between policy and its implementation. First, as students grow older, they spent less time on STEM education (Guan & Cai, 2018). This is because students tend to experience less academic stress in these years than in other years. For example, students in their final year of senior high school face the stress of preparing for examinations that will allow them to progress to higher education. Middle

schools primarily focused on students aged 12-14 when offering opportunities for STEM education in most schools, while high schools targeted year 11 (Guan & Cai, 2018). At the ages of 12-14, the total amount of time spent on STEM education per semester (each year has two semesters, each lasting four months) was 24-27 hours, whereas at the age of 16, it averaged 18 hours (Guan & Cai, 2018).

Second, those students are not taught STEM education because it is not an examined course; The policy in China wants to promote STEM education because it can help develop multiple skills for students. However, the current education system in China places an emphasis on examinations rather than development. Thus, children are being taught to spend more time on courses that are examined rather than subjects like STEM education, which can develop various skills when students engage in problem-solving activities. This might be when creating STEM education policies, the government primarily uses authoritative tools (top-down administrative directives) and capacity-building tools (investing in supporting laboratories and training teachers), according to a textual analysis of the country's STEM education policies for primary and secondary education from 2016 to 2023 (Jiwei, 2024). However, there are still very few tools for systemic change and incentives (Jiwei, 2024). Measures such as providing teachers who participate in STEM education with monetary incentives or awarding them extra points on teacher qualification exams are examples of incentive mechanisms (Zhang, 2008). Reforming the admissions exam system to include STEM education content in exam subjects is one way to implement systemic change (Jiwei, 2024). Consequently, both benefits and disadvantages were influenced by the stark imbalance in policymaking. On the positive side, authority and capacity-building tools make it easier to quickly and widely implement STEM programs across the country. On the other hand, a lack of incentives and systemic change prevents STEM education from becoming deeply accepted, placing it in the background of schools' heterogeneous curricula. As a result, its educational impact is not up to par. Among the various skills that STEM can bring, CT has been overlooked, which also aid students in their examinations. Similarly, CT training is often withdrawn from students because it is not included in public exams, despite being a crucial time for their development.

Finally, studies have noted that the development of STEM education in mainland China has taken on a dual-track pattern, where students not only engage in STEM courses within their

schools but also actively seek opportunities offered by external education providers, with competitions proving especially popular (Zhang, 2008). This trend reflects both the public's enthusiasm for STEM and the strong demand for high-quality provision. At the same time, it raises concerns about whether, despite favourable policies and rapid market expansion, the pace and quality of school-based STEM education may be insufficient, leaving students and parents to turn to commercial programmes outside school. Most of these external platforms are operated by private education companies, often lacking system-wide coherence or regulatory oversight (Tengyue, 2024). As a result, some providers place disproportionate emphasis on competition outcomes in order to demonstrate quick results to parents, leading to course designs that drift away from STEM's original aim of cultivating well-rounded competencies, and becoming increasingly utilitarian and short-sighted. Therefore, the dual-track pattern has produced a paradox. Within schools, STEM is promoted as a broad and foundational subject; however, the quality of provision is often inconsistent due to limitations in resources and teaching staff. Outside the school system, STEM is presented as an elite and competition-oriented "enhanced version," one that is accessible primarily to families with sufficient financial means and, in some cases, is further distorted by market-driven goals. Such a barrier might continue to risk widening educational inequality and undermining the fundamental purpose of STEM education itself, posing important challenges for future policy design and regulation.

2.8. Summary and recommendations

In summary, STEM education in China currently follows two main models. The first integrates STEM concepts into existing science-based subjects, allowing students to make interdisciplinary connections, for example, combining computer science with STEM-related content. The second treats STEM education as a separate interdisciplinary subject or as part of thematic projects, such as robotics studies that combine mathematics, IT, and engineering knowledge. Education authorities in both mainland China and Hong Kong recognise the growing importance of STEM education; however, its implementation in secondary schools in China still places greater emphasis on subject knowledge rather than higher-order thinking skills, such as CT. Moreover, the cultivation of CT is often postponed until higher education, even though such skills should ideally be developed from an early stage to support lifelong learning. Building on these findings, the implementation of this newly developed teaching model within STEAM education holds particular significance, as it fosters the development of

a broad range of student competencies, such as students' CT. By integrating practical IBL experiences into classroom teaching, the model in this project not only enhances students' abilities but also aligns with national efforts to cultivate innovative talents equipped for the digital era. It thus provides a valuable reference for promoting deeper, skills-oriented STEM learning in schools.

Finally, to address the barriers between policy and implementation, several targeted measures are recommended. First, greater incentives should be provided to teachers who actively participate in STEM education, such as linking involvement to professional promotion criteria, national recognition, or financial rewards. Second, a sustainable and systematic system of professional development needs to be established to ensure that teachers receive continuous training and practical support, rather than relying solely on short-term workshops. Third, curriculum reform should be accompanied by examination reforms that integrate STEM-related components into assessment systems, helping to align policy intentions with actual teaching practice. Finally, regulatory frameworks should be strengthened to ensure quality and equity across both school-based and extracurricular STEM programmes, reducing the over-commercialisation of external providers and ensuring that access does not depend on family income. Overall, the future development of STEM education in China, therefore, depends not only on policy ambition but on the effectiveness of its implementation mechanisms. A balanced approach that combines policy authority, incentive structures, and sustainable resource investment will be essential to bridge the gap between policy design and classroom practice, ensuring that STEM education becomes both equitable and transformative across all regions.

3. Literature review

3.1. Introduction

The aim of this review is first to introduce the process of reviewing the literature and then give details on the content of the literature review. The content includes the background and significance of IBL in STEAM education. The researcher will summarise the development of CT through different forms of IBL and analyse how STEAM education might influence the CT of secondary school students. Finally, the research gap will be highlighted through integrating themes, meanings, and goals.

STEAM education claims to cultivate students' comprehensive subject knowledge and understanding whilst also improving their skills and creativity, and, in turn, promoting innovative talents to meet global demands, such as those in the industry (Wang, 2017). Furthermore, educators have explored creativity because it relies on talent and is challenging to develop directly through education. Interestingly, CT skills can indirectly contribute to learners' creativity and enhance it (Runco, 2003). Meanwhile, regarding STEAM education, IBL is one of the most popular and effective teaching methods used for effective delivery (Perignat & Katz-Buonincontro, 2019). This is built upon students, under the guidance of their teachers, having to acquire their knowledge through finding, exploring, and obtaining a conclusion, which differs from traditional teaching methods, where teachers often provide conclusions for their students (Perignat & Katz-Buonincontro, 2019).

However, most Chinese STEAM education research mainly focuses on educational theory and overseas teaching models (Wang, 2017). This is because STEAM education is in its initial stages in China; the good news is that the number of educators joining the STEAM education sector in recent years has increased. Meanwhile, 'The Core Competencies for Chinese Students' Development' (2016b) indicated that the quality of thinking and the associated abilities with thinking skills are key characteristics required for a well-rounded human being. Overall, this means that studying CT, IBL, and STEAM education is valuable. Thus, this literature review will focus on IBL and STEAM education to determine whether a gap exists between the two concepts in the context of secondary school students' CT in China.

3.2. Methodology for literature review

For this literature review, the main method of references collection was via searching different keyword combinations on the University of Glasgow online library databases, Google Scholar, as well as CNKI (*China National Knowledge Infrastructure*) as listed in Table 5. When using keywords to search the databases outlined in Table 6, such as STEAM Education, secondary school students, CT, IBL, and Chinese STEAM education, 941 results were retrieved. Furthermore, when considering the initial inclusion or exclusion criteria outlined in Table 7, 340 papers were retrieved, and of these papers, 191 are within the selected review period (2010-2015). After went through all the abstracts, 36 papers are relevant and have been chosen for close readings and analysis.

Google Scholar
Glasgow University Databases
Glasgow University online and offline library
International Journal of STEM Education
Baidu Scholar (Chinese version Google Scholar)
CNKI (Chinese National Knowledge Infrastructure)

Table 5: Databases searched for Literature Review

Titles and abstracts from database searching	941
Research papers remaining on application of initial inclusion and exclusion criteria	340
Available publications reviewed inclusion criteria	191
Publications related to the thesis and have been analysed in this chapter	36

Table 6: Numbers of publications selected and retrieved in total

Review of support teaching	Inclusion	Exclusion
Review period	2010 - present	No date- 2009
National or international scope	English language & Chinese language	Language that is not English or Chinese
Type of data	Theoretical review Empirical review	Personal opinions
Age range	Aged 12 – 18 (Secondary school students) In China, secondary schools including middle school (aged 12-15) and senior high schools (16-18)	0 – 10 19 – other
Adult support	Adults whether paid or unpaid who provide support in schools. In service teachers Support teachers who have training in STEM/STEAM/STEM+ Education.	Pre-service teachers Parent or volunteers Counsellors Educational psychologists Primary school's staffs Higher education staffs
Study Subjects	STEM/STEAM/STEM+ education Computer science Information technology Mathematics Biology Physics Chemistry	Language based subjects History Arts Music PE Non-STEM subjects
Institution type	Mainstream Secondary Schools	Special needs schools Primary Schools Higher Education Vocational Schools After school classes

Table 7: Review of selected publications

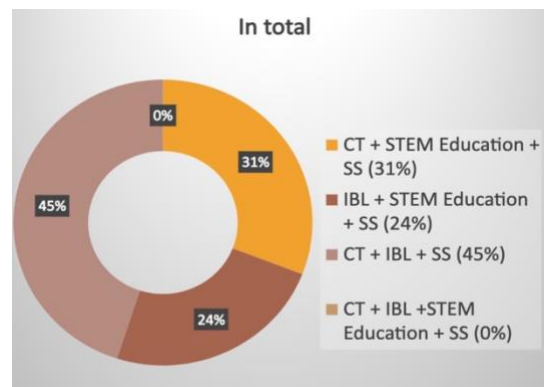
Table 8 shows that several articles investigate the CT and STEAM education of secondary school students. After reading the articles, nearly half of them concentrate on a single subject rather than integrating multiple subjects, such as science, mathematics, biology, physics, or information technology. There appears to be a gap in the research that focuses on a combination of STEAM education, such as mathematics and engineering, and their links to CT and IBL; Very little research has been published between 2010 and 2025 in the United Kingdom about secondary school STEAM education, CT, and IBL, with a total of 25 results appearing. The

search results of research on CT in secondary schools' STEAM education yielded 22 research studies from 1999 to 2025, with a further limitation to 13 studies from 2010 to 2025 as showed in Table 8. Here, only four studies focused on the development of CT in secondary school STEAM education, two in higher education, two in language study, and five were not relevant in their context. For IBL in secondary school STEAM education, there were only six. When this method was applied to U.S. studies, a greater number of outcomes emerged, with a total of 139 published articles in the past decade alone. To be precise, 57 studies focused on the development of CT among secondary school students in STEAM programs. Overall, there were very few results that specifically addressed CT of IBL in STEAM education, showing that there is a research gap in current research.

Search Terms	CNKI	BEI	ERIC
CT + STEAM Education +SS	7	13	39
IBL + STEAM Education + SS	16	8	22
CT + IBL + SS	4	4	78
CT+IBL+STEM Education + SS	0	0	0

SS: Secondary School; IBL: Inquiry-based learning

Table 8: Number of publications in CNKI (China), BEI (UK) and ERIC (US) from 2010 to present.



3.3. Theoretical foundations

3.3.1. Constructivist learning theory

Constructivist learning theory emphasises students' learning, which involves building knowledge by connecting new ideas to their past experiences and personal beliefs. In this process, learners take the lead, not teachers. Each learning activity provides students with an opportunity to review, adjust, and refine their existing knowledge. Moreover, as constructivism encompasses cognitive (Piaget, 1977) and social elements (Vygotskij & John-Steiner, 1979), IBL can be used to support teaching activities that work towards supporting cognitive constructivism (Hmelo-Silver et al., 2007). This is because IBL can provide opportunities for learners to engage in and construct their cognitive knowledge by linking experience and new knowledge, such as asking questions, conducting experiments, and examining hypotheses or phenomena (Bybee et al., 2006; Dewey, 1938). Besides, constructivism in IBL emphasises the

creativity, purpose, situation and sociality of learning (Brown et al., 1989). Piaget's (1977) view of cognitive constructivism argues that creativity, or learning initiative, means learners should actively process any incoming information. It also requires teachers to support their students in activating such initiative and enthusiasm. For teachers to engage their students, they need to remind them of prior knowledge. The reason is that prior knowledge is the foundation for future learning in Vygotsky's (1978) theory of scaffolding. In this view, knowledge is not simply delivered by the outside world, but rather built through exploration and shaped by what students gain from experience. Piaget and Cook (1952) also emphasised that students learn more effectively when they can connect new information to existing knowledge. Similarly, Ausubel's (1963) theory of meaningful learning suggests that learners are more likely to retain new ideas over time when those ideas are linked to what they already understand. Because it stimulates pre-existing neural networks, which makes it simpler for pupils to comprehend and remember new knowledge (Brod et al., 2013).

Human learning cannot be separated from the interaction of society, which explains that learning is situational and social (Vygotskij & John-Steiner, 1979). Here, the learning needs of students must be considered because they are also situational and differ depending on the learning activity (Vygotskij & John-Steiner, 1979). Learners should not only understand the subject knowledge but should also be able to apply the acquired knowledge to solve problems in real and complex situations. Meanwhile, this reinforces the importance of prior learning and applying knowledge to fulfil students' learning needs. By incorporating real-world situations that are relevant to students' experiences, teachers can support them in making connections and deepening their understanding of the curriculum knowledge (Piaget & Cook, 1952). Lastly, in a retrieval practice study, previous knowledge aids pupils in retrieving information from memory (Roediger III & Karpicke, 2006b). When students are exposed to real-world circumstances related to what they have studied, they are more likely to recall this material from memory and demonstrate their understanding. Meanwhile, according to Vygotsky's (1978) social constructivist theory, learning occurs through interactions with experienced individuals, participating in group discussions, and problem-solving. Besides, the social learning theory, developed by Bandura and Walters (1977), strongly emphasises how social reinforcement and modelling affect behaviour and how knowledge and skill development are acquired. It explains that people can acquire knowledge by observing and imitating the actions of others. In other words, collaboration among students during the study is meaningful. By working together,

students can engage in joint problem-solving, share their understandings and ideas, and receive feedback from peers. This interaction helps them build their understanding and internalise new knowledge, making it more meaningful and lasting.

Therefore, according to the above theory, there should be four essential conditions when introducing IBL guided by constructivism in STEAM education in this project: 1. Prior knowledge, 2. Problems in real-world situations, 3. Collaboration, and 4. Teachers' support. It will be based on constructivism, creating links between teaching activities and real-world problems, aligning the students' collaborative study with a clear purpose, helping them receive knowledge easily, and be enabling them to retrieve it from memory. Ensuring real-world applications support the learner's discovery and formulation of applicable solutions to problems, thus establishing a stimulus for learning activities and nurturing students' initiative. Teachers should provide students with appropriate and necessary aid at the correct times, such as reviewing prior knowledge, demonstrating concepts, posing questions, and offering guidance. Only in this way will the learners be encouraged to examine and accumulate different ideas, which is more conducive to exploring and integrating what they have learned and helping construct meaningful associations. For example, in the participating school, during semester one, students create an instrument in groups, such as the ukulele, to learn to play a piece of music throughout the year. In this example, making a ukulele is an application of the constructivist approach. The teacher references simple musical instruments that can be found in everyday life. The students are then guided to build their knowledge by designing, making, and using it in a teaching activity that corresponds to STEAM education. However, in the usual lessons in the participating school, students have few chances to develop CT. Therefore, the researcher proposes using a new integrated model to provide students with more opportunities to develop their CT.

3.3.2. The Learning cycle model

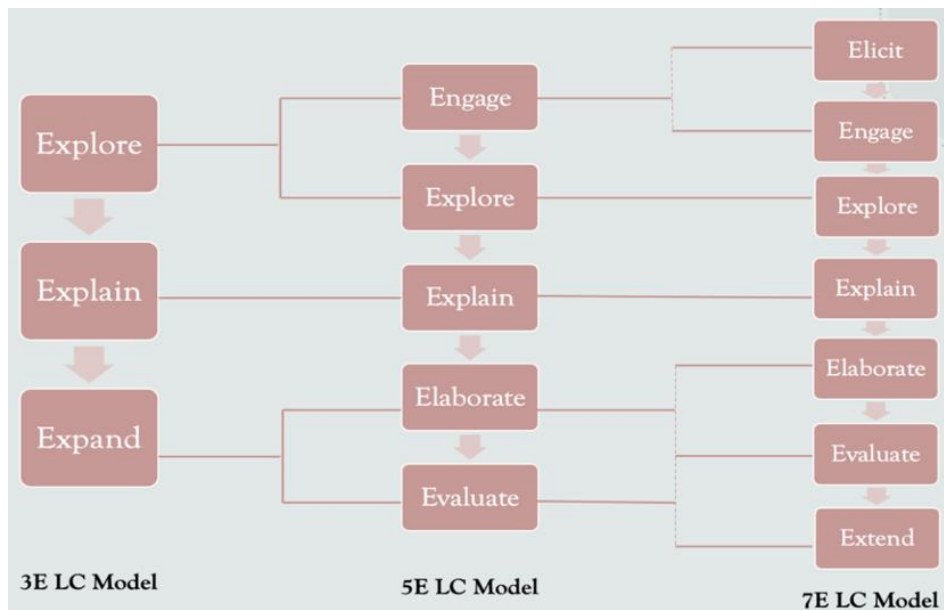


Figure 2: 3E, 5E and 7E LC models (Karplus & Thier, 1967; Bybee, 1990; Eisenkraft, 2003)

The concept of the learning cycle, commonly referred to as the "3E model", can be traced back to the Science Curriculum Improvement Study led by Karplus in the 1960s. Drawing on Piaget's (1952) theory of cognitive development, Atkin and Karplus (1962) outlined a guided discovery approach that laid the groundwork for the LC. Later on, Karplus and Thier (1967) subsequently formalised this cycle in three steps, which includes Exploration, Invention, and Application. In later literature, these stages were reframed with "E-words" as Explore, Explain, and Expand, giving rise to the so-called 3E model. Subsequent frameworks, such as the 5E and 7E models, were direct extensions of this original cycle. The LC model is a teaching and learning framework that describes the phases involved in acquiring information and skills (Karplus & Thier, 1967). It proposes that learners progress through several phases as they acquire knowledge and experience, reflecting on what they have learned and applying it in new contexts. The cycle continues to repeat itself, continually increasing knowledge and skill. As shown in Figure 2, the 3E LC model includes Engage', Explore, and Explain phases, which was created to support inquiry-based science instruction and promote active student involvement. The paradigm promotes a practical and experiential approach to learning, leading to a deeper understanding of the subject matter. However, the 3E LC model, as a simple experience cycle, did not cover the acquisition of knowledge that is required (Nicol et al., 2020). Therefore, to meet the demand for additional evaluation during the educational process and to give a more comprehensive and structured approach to learning, the 5E LC model was first

developed by the Biological Sciences Curriculum Study (BSCS) team, led by Bybee (1990). As shown in Figure 2, the 5E is derived from the 3E by adding three elements: Engage, Elaborate, and Evaluate. Bybee further emphasised that it is based on best practices in teaching and learning as a model to access knowledge through reflection and interaction (Bybee, 1997; Bybee et al., 2006). Following this, the 5E LC model has been widely adopted in science education and has also been applied to other subjects (Nicol et al., 2020). Based on the 5E, Eisenkraft (2003) expended it into the 7E, arguing that to help students review their previous knowledge before conducting inquiry, it is necessary to include the Elicit step, allowing students to link their prior knowledge to the new knowledge in the class. As Ausubel (1968) emphasised, the main factor influencing learning is their knowledge background; understanding their prior knowledge is necessary for guiding effective instruction. Meanwhile, Eisenkraft (2003) added the Elaborate and Extend sections at the end of the 7E LC model to enhance the transferability of what students have learnt. It stimulates students to 'transfer learning', arguing that transfer of learning occurs only when tasks share common elements (Thorndike, 2013).

In conclusion, the LC model begins with 3E, the basic foundation, and then the 5E, which is based on 3E, generally meets the inquiry-based constructivist learning goals; nevertheless, it lacks two aspects: eliciting and transferring knowledge outside the classroom. Thus, based on 5E, in the 7E, the two meaningful differences are reviewing previous knowledge and transferring knowledge to other situations. Hence, Marfilinda et al. (2020) highlighted that the 7E LC model can enrich students' achievement while also supporting the development of science process skills and moral reasoning. These findings suggest that the LC model contributes not only to improved academic performance but also to the increase of broader capacities that are central to science and STEAM education. Owing to this premise, the researcher will combine the 7E LC model and IBL to conduct a well-planned new model in the experimental group to examine students' performance based on assessing their CT. In 3.6.2. The revised 7E IBL model in this project, the researcher will introduce and justify a new revised framework for STEAM education.

3.3.3. Inquiry-based learning

IBL is a pedagogical approach centred on the investigation of questions, problems, or scenarios, enabling students to construct new knowledge through systematic exploration (Pedaste et al., 2015). It is a simplified version of the process used by scientific researchers when conducting experiments in an attempt to gain new knowledge (Keselman, 2003). It enables students to acquire foundational knowledge and frameworks of new disciplines within a short time period by becoming researchers themselves (Urdanivia Alarcon et al., 2023). For example, through theoretical or practical activities, students engage with learning aims by posing and answering relevant questions (Goodchild et al., 2013). This is carried out in a cycle of series problems: first, the problem (or learning aim) is identified, data on it is collated, and then analysed in an inquiry process. The students develop practical responses based on what they have learned and then refine this knowledge by sharing it with others (Dana et al., 2011). At the forefront of IBL is the emphasis placed on practical activities, and a turn away from the traditional classroom dynamic of teacher-to-student-centred learning; that is, the teacher has the role of assisting and guiding the student on their learning journey (Ibrahim et al., 2017).

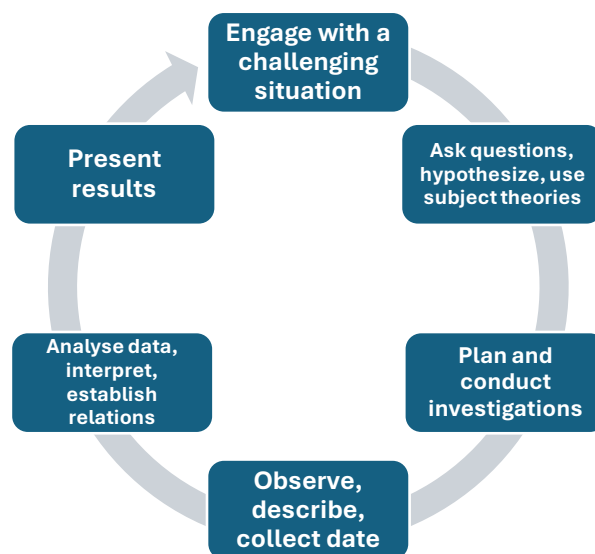


Figure 3: Inquiry-based Learning (Lembens and Abels, 2016) cited by (Hofer, et al., 2018)

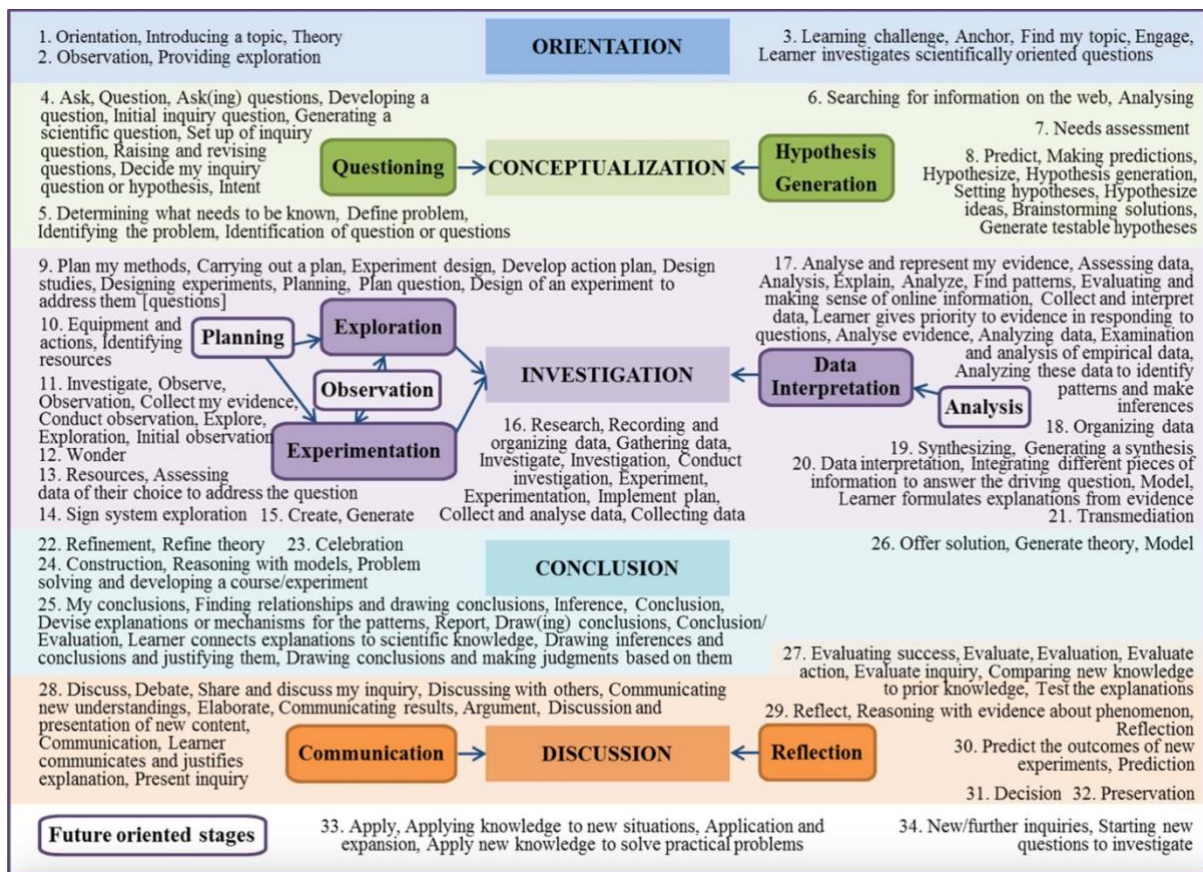


Figure 4: Phases of IBL (Pedaste et.al., 2015)

IBL normally comprises five or six critical steps, as depicted in Figure 3 and Figure 4. It employs systematic approaches to exploring and acquiring new knowledge by posing questions to the learners (Pedaste et al., 2015). These questions are formed within a circular series of steps described by Hofer et al. (2018) and Pedaste et al. (2015): first, the problem (or learning aim) is identified; after that, it is the experiment, collecting relevant data, and analysing the data. The final step is presenting the findings of the experiments and discussions with peers. This final step enables students to develop practical responses which can be refined through sharing with others (Dana et al., 2011).

3.4. STEM education theories and pedagogical frameworks/models

3.4.1. In Western contexts

As the patriarchies from which STEM education was initially proposed and promoted, Western countries like the United States were first to establish and develop a series of pedagogical standards and norms for this emerging curriculum. Educational researchers and practitioners in Canada, Australia, and European countries, such as the United Kingdom, have also developed instructional frameworks tailored to their respective educational systems to support the implementation of STEM education. This has encompassed several well-known pedagogical methods that have become prevalent within the field of STEM education, including IBL/EBL (Inquiry/Enquiry-Based Learning) (Pedaste et al., 2015), PBL (Project-Based Learning) (Thomas, 2000), Problem-BL (Problem-Based Learning) (Barrows & Tamblyn, 1980), and instructional frameworks the 3E/5E/7E LC Model (Bybee, 1990; Eisenkraft, 2003; Karplus & Thier, 1967). The above models or frameworks are broadly applicable, not only for STEAM or integrated STEAM education, but also for some humanities-oriented subjects. For example, during a literature review, the researcher found numerous applications of IBL in the teaching of English linguistics. In the context of robust support for technological advancement from both society and governments, STEM education has been incorporated into national and regional development strategies in several places. This has generated a growing focus and investment in integrated STEM education, motivating the continuous emergence of novel teaching models and frameworks focused on interdisciplinary instruction.

Todd et al. (2016) incorporated various learning theories and fundamental concepts within STEAM education, offering an integrated framework that seeks to support further research on integrated STEM education. This framework aims to provide an instruction manual for STEM educators and establish a research agenda in the area. A conceptual framework provided by Falloon et al. (2020) aligned the features of integrated STEM education to deliver valuable, actionable guidance for planning and undertaking it in classrooms. It sought to synthesise and underscore the crucial elements, different input points, curricula, and subject strategies necessary to enable the delivery of STEM education within classrooms and increase STEM literacy in K-12 students. The pedagogical model of the SML (STEM Maker Lesson) delivers a more comprehensive integrated curriculum, modelling an improved understanding of mathematical knowledge within STEM education (Bertrand & Namukasa, 2023). It includes

four core steps: 1. Building curiosity; 2. Collecting data and facts; 3. Making and refining; 4. Reflecting, applying, and thinking forward (Bertrand & Namukasa, 2023).

3.4.2. In Asian contexts

To date, there have been considerably fewer studies focused on STEM education in Asian regions than those concentrated on Western countries, with the U.S. receiving the most attention (Ahmed & Mudrey, 2019). As a result, studies investigating the frameworks for STEM education implementation in Asia are scarce. One of the few examples is the Korea Foundation for the Advancement of Science and Creativity's (KOFAC, 2016) introduction of a framework for directing STEM lessons, which was centred on three core steps: 1. the "Presentation of Situations" for bridging problems to real-world contexts, 2. "Creative Design" for critical and creative problem-solving thinking, and 3. "Emotional Touch" for providing interest and motivation to activities. A further example is the Education Bureau (2016) of Hong Kong, which proposed two approaches for implementation STEM education. The first approach is tailored for novice teachers and recommends the inclusion of additional elements in certain topics, while the second comprises the integration of various STEM elements into a single project, an approach which is more suitable for experienced STEM teachers.

Lin and Tsai (2021) developed five pedagogical strategies—scaffolding, tutoring, engagement, argumentation, and modelling for interdisciplinary STEM courses. Each of these strategies is designed to complement hands-on activities, inquiry-based learning, or project-based learning. Additionally, engineering has been recognised as a key practical element in Japan's approach to STEM education. The design process typically involves steps such as designing, building, and testing, which play layered roles based on what students need to know and do for effective engagement in engineering tasks (Yata et al., 2020) . Building upon the framework provided by Yata et al. (2020), Sujarwanto and Sanjaya (2021) incorporated policies and culture from Indonesia by considering the relevant relationships between science, technology, and mathematics.

Globally, STEM education frameworks in both Western and Asian contexts tend to emphasise specific priorities but often lack full integration due to narrow or singular development goals. In addition, the cultivation of students' CT has received limited attention in many of these

models. To address this, future research should build on existing frameworks by combining the strengths of different approaches to develop a more cohesive and comprehensive model for STEAM education. Employing the case study of a participating school in Hong Kong, this study seeks to investigate a novel, highly integrated model to both emphasis the cultivation of STEAM education and attend to the integration of students' interdisciplinary knowledge and ability to utilise knowledge in ways that surpass the confines of the classroom (by enhancing CT).

3.5. CT and IBL in STEM education contexts

3.5.1. The development of CT in STEM education

As listed in the 3.2. Methodology for literature review, the literature in this area is limited; however, there are still some projects that have looked at the development of CT in STEM education. He Shasha (2019) published her research on CNKI highlighted STEM education has helped students improve their CT dispositions in two elements, the ability to seek truth and maturity on recognition. She is the first Chinese researcher who indicated that STEM education could help students develop their CT dispositions, although the growth mentioned in the experiment was not particularly significant. In the same year, Zhuo Xuemei (2019) used CCTST-2000 (the California Critical Thinking Skills Test - 2000) to test students' CT skills level in STEM education; it also gives suggestions for improving CT skills through observations of teachers' teaching. The result shows the CT skills of students still needs improvement, most of the learner's understanding of CT is rather unilateral, with some of them believing that the key to CT is 'judge', which is different from 'analysis, evaluation, reflections and summaries' (Zhuo, 2019).

3.5.2. The use of IBL method in STEM education

In the early twentieth century, Dewey (1938) was the first to propose the concept of 'inquiry pedagogical theories', also known as the 'learning-by-doing theory'. In the realm of science education, 'the doing' placed importance on students developing CT and knowledge through hands-on activities as a main teaching tool. Dewey (1938) outlined five stages of inquiry-based teaching: recognising a problem or difficulty, clearly defining the challenge, proposing possible solutions, testing those solutions, and confirming the hypothesis through observation or

experimentation. Thus, all these steps of the scientific process will lead the student to gain knowledge through IBL (Dewey, 1938).

After World War II, the field of science education globally underwent rapid changes as it received increased attention from schools and governments (Zhang, 2008). In pedagogical studies, achievements were made in the development of new teaching theories and knowledge of human cognitive processes (Zhang, 2008). In 1961, the renowned American educational psychologist, Jerome Bruner, put forward the theory that when a student constructs a framework of scientific knowledge on their own, they thereby cultivate their propensity for scientific inquiry (Bruner, 1961). A pioneer who advocated for the inquiry-based constructivist learning theory, Bruner believed that students were capable of furthering their own knowledge and ability to discover more by actively seeking specific problems and using discovery-based learning theory to find the answers for themselves (Bruner, 1961).

Contemporaneous to Bruner were the theorists Dewey and Schwab who developed the disciplinary structure theory, presenting inquiry-based teaching approaches in greater depth, particular for science education (Schwab, 1960). The goal of science education is not merely to acquire knowledge, but to develop stronger skills in scientific inquiry. This includes recognising a key feature of science: that scientific knowledge, in most cases, is grounded in observation, experimental evidence, rational justification, and a spirit of CT (McComas & Olson, 1998). Hence, a laboratory is the best setting for effective science education, giving students a more immersive experience of scientific processes by taking part in experiments (Hofstein & Lunetta, 2004). This aligns with the common difficulties and frustrations encountered as part of the scientific process. The resulting joy and sense of achievement when students make discoveries strengthens their inquiry skills and also their keen to study. Putting this into practice, Schwab went on to edit a high school-level biology textbook, which became a great success throughout the US (Schwab, 1960). This set text served as the basis for subsequent researchers to create a variety of other scientific curricula in the fields of mathematics and information technology (Schwab, 1960). Schwab's theories and inquiry-based methods have been highly influential and are still the basis for science education today (Shen, 2018).

With the development of IBL method, different viewpoints have emerged from the academic community on the use of it. Researchers such as Kirschner et al. (2006) point out that teaching methods with minimal guidance and instruction are ineffective, and this includes IBL, and other forms of PBL, as well as discovery learning and constructivism. Similarly, a four-year Norwegian study, the LCM (Learning Communities in Mathematics) project, reported by Goodchild et al. (2013) set out to research high school maths teachers specifically employing IBL activities find that withholding disciplinary knowledge from students, results in failing to reach expected outcomes. Kirschner et al. (2006) highlight that the over-emphasis on practical knowledge and ignoring the importance of a sound theoretical basis is one of the important reasons that IBL becomes an ineffective teaching approach. In addition, they emphasise that it is especially damaging to new students who have no theoretical grounding in the subject (Clark et al., 2012). Based on these studies, one can conclude that there are two main reasons for the failure of using IBL in STEM education. On the one hand, learners lack basic disciplinary knowledge; On the other hand, teachers are over-reliant on the exploration and activities that can provide learners with academic, skills and abilities achievement. Heindl (2020) builds on this by stating the necessity of adequately preparing teachers and students before embarking on IBL in science education. Meanwhile, from previous experience, the teachers from the LCM project learned from the mistakes and gave the students appropriate guidance alongside their practical experimentation (Goodchild et al., 2013). It included explaining relevant terms and giving the students appropriate leading questions. In contrast, the students were successfully able to explore the new knowledge with a combination of IBL with guidance from their teachers (Goodchild et al., 2013). Therefore, the success or failure of IBL is closely linked with adequate preparation of teachers and students. Meanwhile, to maximise the educational outcomes of IBL in STEM education, teachers require a comprehensive curriculum design.

A growing number of studies have highlighted the suitability of IBL in teaching science education. For example, Heindl (2019) published a meta-analysis of research into the use of IBL in science education, showing that when applied to students from a young age, it has positive learning results. Heindl's meta-analysis of 13 studies from the period 2011-2017 compared the academic performance of science students who either received traditional or inquiry-based teaching methods (Heindl, 2019). The outcome suggests that IBL methods are superior to traditional methods and have a substantial beneficial impact on student performance and academic achievement (Heindl, 2019). Similarly, Liu et al., (2022), in their systematic

literature review of 34 studies from the period 2000-2019, show that the majority of them highlight positive effects of mobile based IBL used in science education in secondary schools. Although, the positive impact overwhelmingly outweighed the negative, the authors point out there are few studies on the use of mobile learning to support IBL (Liu & Pásztor, 2022). In conclusion, IBL could be a successful teaching method in STEM education to improve the teaching quality and to cultivate students' subject knowledge and different learning skills.

3.5.3. The development of CT through IBL

The latest decade has shown a remarkable development of CT through different types of IBL. Sam (2024) highlighted in his systematic literature review that IBL has a positive impact on students' CT, motivation, and academic performance when combined with supportive learning environments and teacher training. Meanwhile, scholars Jainal and Louise (2019) conducted a study in Indonesia to investigate high school students' CT skills in their chemistry classes. They used Macromedia flash and adopted a guided inquiry-based approach; this was supported by teacher-led education. The findings revealed that those students who were taught using guided IBL teaching methods had a much higher CT skills than those taught using traditional methods (2019). Hence, Perdana et al. (2020) also carried out a study in a secondary school in Indonesia; and confirmed that students' critical and creative thinking skills improved significantly when the ISC (Inquiry Social Complexity) learning model was implemented. Moreover, scholars Lu et al. (2022) studied a group of 53 secondary students in Taiwan and their results indicated that students' CT and scientific inquiry ability outcomes notably improved after one year of being taught by CDI (Critique-Driven Inquiry) teaching activities. Thus, according to the above studies, there are several reasons that may explain why the three cases outlined above were successful in increasing students' CT. The core explanation is that firstly, all three studies revealed that the students had been taught through the IBL method. For example, ISC learning model from Perdana et al. (2020) integrates both the inquiry teaching model and social complexity. This is similar to the process of the IBL approach. The CDI teaching method by Lu et al. (2022) gives learners the power to construct knowledge through numerous inquiry-based scientific activities. More specifically, this method gets students to construct questions to ask, as well as propose their own hypothetical solutions. It also involves students collecting and analysing their data and coming to conclusions based on the research findings. Considering this, the CDI teaching method helps students to develop their scientific and chemistry-specific STEM knowledge (Lu et al., 2020). Secondly, IBL helps students to improve their scientific

concepts - this is because students' self-directed inquiry strengthens their CT (Lu et al., 2020). CT contributes further to students' understanding of scientific concepts in the following aspects of scientific inquiry: questions, investigation, reasoning, communication and explanation, assessment, and novelty (Perdana & Rudibyani, 2020). It is similar to IBL because it contains the above process, and CT could be a main factor during learning that can help learners with their problem-solving abilities.

The following investigations also underlined the benefit of IBL in CT, although the results were not as significant as the studies above (Maknun, 2020; Pahrudin et al., 2021; Tang, 2017). Scholar Tang (2017) spent two years studying year six (aged 12) and year seven (aged 13) students in a Chinese secondary school. These students were primarily taught through scientific inquiry micro-activities in STEM subjects. Once the researcher had observed both the control and experimental group, he was able to conclude based on the results that those students who participated in inquiry micro-activities had better CT skills (Tang, 2017). Within the several metrics in CT skills, students were more advanced in their analytical skills, systematic skills and in their cognitive maturity when compared to the control group who had only experienced a traditional education (Tang, 2017). Pahrudin et al. (2021) conducted a quantitative study of secondary-level physics classes with the aim of determining the extent to which students' CT abilities had changed as a result of STEM-based IBL. More specifically, the scholars studied two groups of 50 secondary students in Indonesia. The results revealed that the STEM-based inquiry model had a beneficial effect on students' knowledge of physics concepts and their CT skills (Pahrudin et al., 2021). However, the increase in pupils' CT skills was not very significant. Maknun (2020) also states that when compared to traditional teaching methods, guided inquiry learning improves students' CT skills and their understanding of physics concepts. However, his research was based on a small sample of 28 students, and one particular physics concept (Maknun, 2020). Considering this, it is important that more research be done with a larger sample and a variety of curriculum topics. Pahrudin (2021) identifies two main reasons why STEM-based inquiry learning can improve students' CT. First, it encourages students to take responsibility for their own learning; Secondly, he notes that STEM-based inquiry learning provides learners with a series of inquiry steps that allows them to study through a more practical experience; for example, by asking questions, making hypothetical solutions, designing plans, and examining and communicating with peers (Pahrudin et al., 2021). Moreover, during inquiry process, it also gives students the freedom to observe tasks

individually under the guidance of their teacher and this allows them to express their ideas and thoughts openly with their classmates, as well as raise any issues they have and provide suitable solutions (Maknun, 2020). Pahrudin (2021) further brings attention to the fact that pupils in the experimental group learned in a primarily student-centred way. Students in this group gained more theoretical knowledge about the subject and learned how to use scientific equipment through a hands-on understanding of physics concepts through practical experiments (Pahrudin et al., 2021). Worth mentioning is that in Tang's (2017) study, there was a gender divide with boys in the experimental group exhibiting greater gain in CT skills than girls. It means boys may be more easily influenced by science inquiry activities.

However, it does not mean the implement of IBL definitely could improve students CT, because teaching activities have other complications. Ren (2014) reports a case study conducted in a Chinese high school biology class where the teacher used IBL to guide students through a discussion on the safety of genetically modified foods. However, the results from the study provided no clear conclusions of the impact of the lesson on CT of the students (Ren, 2014). There are several explanations for this, the most important one is insufficient time for students to come up with more conclusive evidence of the new subject knowledge; and a small group of students did not acknowledge what to do during the inquiry activities (Ren, 2014). Overall, to increase students' CT through IBL method requires an appropriate teaching strategy, specific curriculum knowledge and sufficient time.

3.6. Integrated 7E IBL model and theoretical framework

Building on the findings from the literature review above and the theoretical foundations of the LC model and the IBL approach, this study presents a revised integrated model, the 7E IBL model, specifically designed for STEAM education. The preceding sections have reviewed the key theoretical and empirical insights, and this chapter therefore closes by positioning the proposed model within this context. The details of the revised 7E IBL model will be outlined in the following section, as well as the theoretical framework guiding the study.

3.6.1. Linking the IBL method with the 7E LC model

According to the literature review, as shown in Figure 5, the link between the 7E LC model and IBL is that the IBL cycle (except presentation phase) is similar to the 'Engage', 'Explore', and 'Explain' sections in the 7E LC model. The reason for these three extra steps and how these

contribute to developing CT will be discussed in the following section. Meanwhile, the differences between the 7E LC model, the IBL method, and the first draft of the 7E IBL model will be listed in Figure 6.

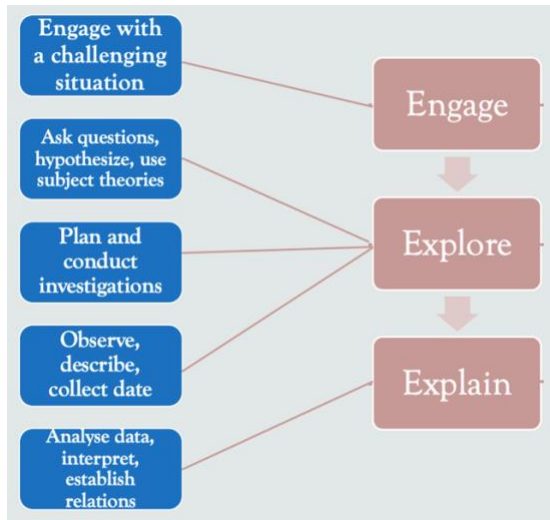


Figure 5: The link between IBL and 7E LC model

3.6.2. The revised 7E IBL model in this project

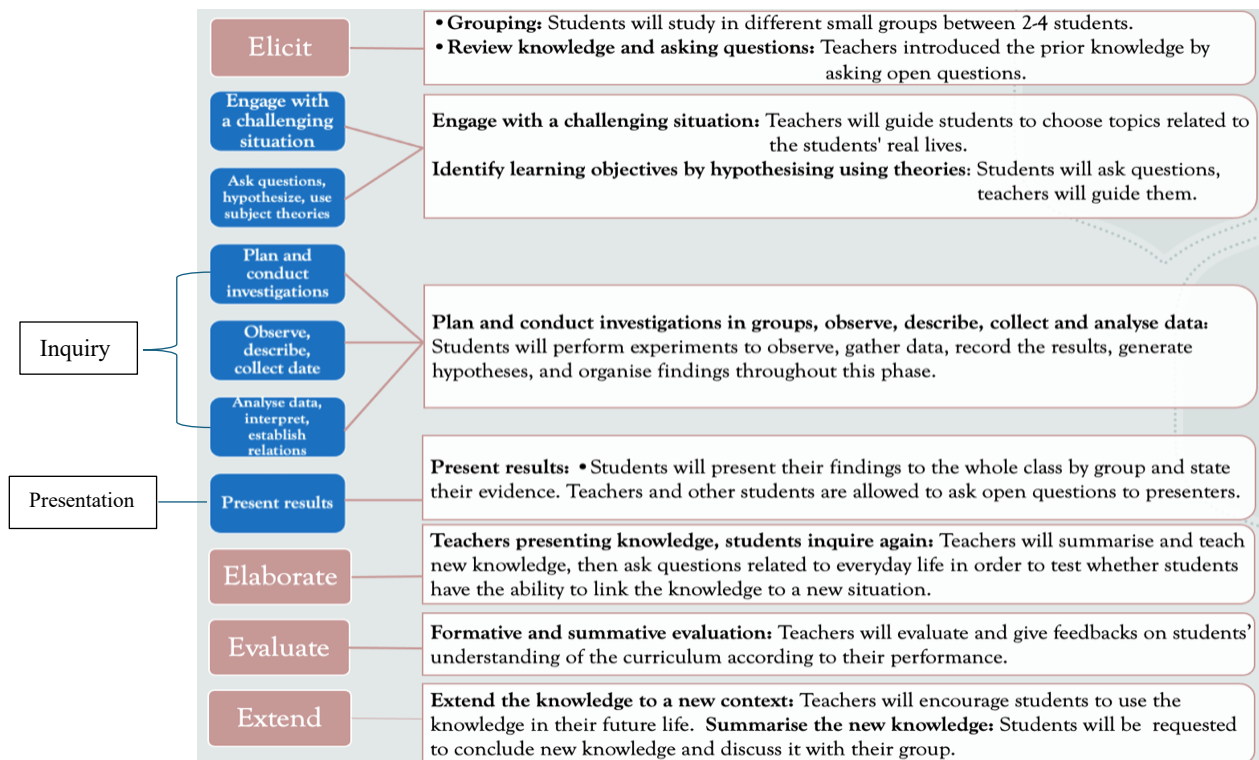


Figure 6: The first draft of the 7E IBL model according to 7E LC model and IBL

In this section, the researcher will explain how to adopt the first draft of the 7E IBL model by integrating the 7E LC model with the IBL model. Figure 6 shows the first draft of the revised learning model called the 7E IBL model, in which the researcher has incorporated IBL model by adding four steps, Elicit, Elaborate, Evaluate, and Extend, from the 7E LC model. There are three main reasons for the revised theoretical framework of 7E IBL. 1. Review the prior knowledge to provide a foundation for students to start the inquiry. 2. The transfer of new knowledge outside the classroom encourages students to reuse the knowledge so that they can remember it longer. 3. During the last three sections help students to repeatedly use and develop CT.

The **Elicit** process allows educators to include the required prior knowledge organically and to introduce new subject matter fluidly (Goodchild et al., 2013). Students are encouraged to form study groups of three to four rather than work independently. An adaptable beginning to this approach would involve educators simulating student conversation with an open question/problem that they want to explore (Eisenkraft, 2003). The ideal question would be one to which there is no correct answer, and teachers would be required to highlight that an agreement does not need to be reached. In IBL model, the **Engagement** process intends to practice the use of CT by asking questions and offering hypotheses. Then, each group will decide on several questions/problem related to everyday life depending on the learning objective raised by their teachers. The students will finally use the guidance to decide what to inquire about, which the teachers will review.

Following the Engagement stage, four steps in the **Inquiry** process are undertaken, as shown in Figure 6. These steps enable the inquiry stage to unfold, underpinned by inquiry-based activities which require students to plan, conduct a scientific experiment and find answers with evidence to support their hypothesis or to offer a new answer to their questions. In this part, teachers should provide appropriate support when necessary, such as by offering demonstrations and guidance. Bybee (2006) explained that the inquiry activities enables learners to examine and accumulate different ideas, which is conducive to exploring and integrating prior learning to construct meaningful associations. Meanwhile, same as Duran & Duran (2004) state, the exploration in this inquiry process is a hands-on phase that is student-centred and geared at developing and fostering their process skills and CT. This is because they can practise different metrics of CT required during inquiry. For example, the ability to analyse

and numerate the data during the experiment (more details will be introduced in Discussion Chapter).

After the inquiry, a group-led **Presentation** and explanation of the results occurs; ideally, students should be able to clarify their questions, share how they answered them, and provide evidence (Prince et al., 2012). After the presentation, teachers and other students can ask questions to the presenting group, enabling communication according to their work. Therefore, they will practice CT during the presentation and explain the answers to others' questions.

In the **Elaborate** stage, teachers will encourage students to apply the new knowledge learned from inquiry activities in related scenarios within the classroom. For example, after students have learned how to use a 3D printer to print one part of the robot, teachers then ask them to design and print a geometric puzzle, which requires learners to adjust parameters and refine the precision of their models. Such tasks deepen comprehension by encouraging students to transfer what they have learned to slightly different but closely connected contexts, ensuring the knowledge is practised and strengthened.

Next, during the **Evaluation** stage, students are encouraged to assess their own learning and consolidate their understanding through both teacher feedback and peer review. Explicit reflection on the inquiry process and their initial hypotheses is particularly important. This stage also provides opportunities for students to practise a wide range of critical thinking skills and dispositions. For instance, once they have gathered evidence from their inquiry activities, they must analyse and interpret the findings, applying reasoning and inference to evaluate their validity. They then apply deductive and numerical skills to assess the feasibility of the outcomes and determine their effectiveness. Finally, during group discussions, the most promising plan is identified and justified with a clear explanation.

In the **Extend** stage, students are also required to transfer knowledge through mini tasks, similar to those in the Elaborate stage. There are two types of knowledge transfer: near transfer and far transfer. Near transfer occurs when learners apply their knowledge or skills to tasks or contexts that closely resemble the original learning situation. By contrast, far transfer takes

place when knowledge is applied in substantially different or less familiar contexts, and it often necessitates adaptation or integration with new skills (Barnett & Ceci, 2002). For the tasks in Elaborate and Extend, they are all based on near-transfer, as the aim is to help students better understand the new knowledge they have learned and the use of CT, rather than advanced techniques. However, the Extend task is broader; it aims to help students link their skills to practical situations, which encourages the transfer of knowledge outside the classroom and enables them to apply their learning broadly and in more useful settings. Using 3D printing as an example, in the extend stage, students might be asked to design and produce a functional object in daily life, such as a phone stand for everyday use, after learning how to make a robot. Another difference from the Elaborate to the Extend is, in the Elaborate teachers set the tasks (asking them to print another part of the robot), Extend requires students to take greater initiative by posing their own questions (they can decide what they want to create, beyond the phone stand or robot) and developing ideas that connect classroom learning with real-world needs. By doing this, teachers could ask students a question like: 'Now you know how to make a robot using a 3D printer, what else could you make using a 3D printer?' In short, Elaborate focuses on depth within the classroom, while Extend emphasises breadth beyond it. Nevertheless, they are both using the near-transfer tasks.

Finally, the researcher believes that the new 7E IBL model could provide more opportunities for students to practice CT by incorporating the 'elaborate' and 'extend' stages, as well as the entire model, rather than a single cycle of the original IBL approach. As in the Elaborate and Extend, students repeatedly reuse the knowledge they have just learned. Although CT is complicated, it can be developed through time and effort (Paul & Elder, 2007). This is because Elder and Paul (2007) contend that CT skills evolve through a process of "disposition building." Meanwhile, practice and repetition are essential for developing mastery of the abilities and helping one internalise them so that they become an organic part of one's thought process. Dewey (1938) and Scriven (1987) also noted that the more reasoning skills and mental habits one develops, the stronger the CT is, including metrics for CT like recognising, analysing, and evaluating arguments. This is due to the fact that practice develops the mental skills necessary for CT. Thorndike's (1913) theory of learning contends that learning happens when responses and stimuli are connected, where exercise is the most fundamental principle, asserts that these bonds are reinforced by practice and eroded when they cease. Once certain connections are established, students strengthen their understanding by accurately repeating

responses during practice. Thorndike also emphasised that providing feedback enables students to remain motivated and continue improving (Thorndike, 1913). Therefore, it is important for STEAM educators pay attention to the required repetition in practice, whether it is for students to construct new knowledge, embed their learning or enhance their thinking.

3.6.3. Theoretical framework

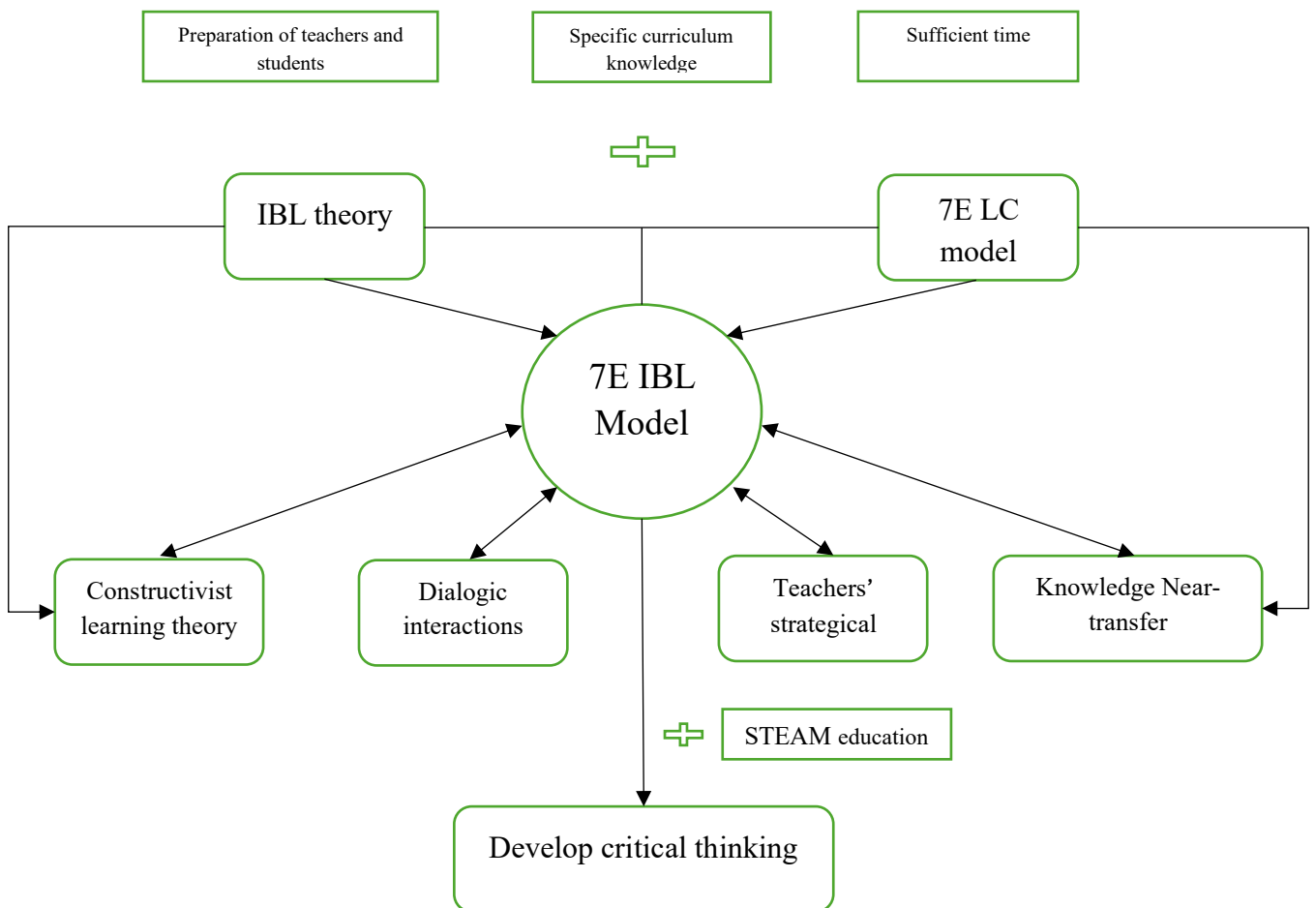


Figure 7: Theoretical framework of this study

As shown in the above Figure 7, it is the theoretical framework according to the literature review. This project is using the 7E IBL method in STEAM education to influence students' CT skills and dispositions.

3.7. Conclusion and research gap

Overall, with regard to the application of IBL in STEAM education, despite the presence of a small number of opposing views, the majority of scholars agree that IBL can be effective when integrated into a well-designed curriculum. However, the direct application of traditional IBL approaches in STEAM education remains limited, particularly in the context of year-long secondary STEAM education programmes. Such programmes are typically characterised by systematic knowledge structures and strong conceptual connections across lessons, whereas basic forms of IBL are more suitable for short-term or single-topic STEAM workshops, or for traditional single-subject courses such as mathematics or information technology. These limitations arise from the coexistence of strengths and weaknesses inherent in IBL. On the one hand, IBL transforms students' learning approaches by encouraging active knowledge construction through inquiry. On the other hand, it places relatively less emphasis on the coherence of interdisciplinary knowledge systems and often lacks systematic support for helping students develop an integrated STEAM knowledge framework. In some contexts, the high degree of learner autonomy required by IBL may also increase students' cognitive load. By contrast, the 7E LC model incorporates stages such as Elicit and Extend, which support the development of more coherent and comprehensive knowledge structures. Nevertheless, the 7E LC model places comparatively less emphasis on practical elements valued in the inquiry process, such as student presentation, communication, and interaction, and provides fewer structured opportunities for sustained peer or teacher–student engagement.

A further review of studies examining the development of CT through IBL indicates that IBL is generally beneficial for enhancing learners' CT. Among different IBL implementations, inquiry-based approaches using Macromedia Flash, the ISC learning model, and CDI teaching methods have been reported as particularly effective, while scientific inquiry micro-activities have also demonstrated positive outcomes. STEM-oriented IBL and guided IBL approaches, although showing relatively smaller gains in CT, were nevertheless found to have a positive impact. Overall, the literature suggests that IBL can promote CT to some extent across different educational contexts; however, its effectiveness largely depends on the appropriateness of teachers' instructional strategies and curriculum design. It is important to note that the above studies reviewed were conducted within traditional classroom settings, and the impact of IBL on students' CT within integrated STEAM education remains underexplored. One key distinction between traditional subject-based disciplines and STEAM education is that STEAM

education places greater emphasis on interdisciplinary integration and inquiry-oriented learning approaches to cultivate students' different skills. Given that STEAM education places a strong emphasis on practical engagement and authentic problem-solving, the researcher argues that the adoption of suitable pedagogical strategies and systematic curriculum design within STEAM programmes may yield more substantial improvements in students' CT.

Finally, research on CT within STEAM education remains limited. Existing studies have reported relatively low levels of CT skills among Chinese secondary school students in STEAM-related contexts, while other research suggests that STEAM education may contribute to the development of certain CT dispositions, such as truth-seeking, albeit with limited impact. Similarly, closer examination reveals that much of this research conceptualises STEAM education as the integration of STEAM principles into individual traditional subjects, such as biology, rather than addressing fully integrated STEAM classrooms. Meanwhile, in the context of rapid technological development, an increasing number of countries and schools have incorporated STEAM education into primary and secondary curricula, making it a growing focus of educational research. Consequently, how to adopt appropriate pedagogical approaches, instructional strategies, and technology-supported inquiry-based learning models within year-long integrated STEAM education at the secondary level to systematically foster students' CT, remains a research gap. In other words, according to the literature review, the research gap is as shown in Figure 8 below: The use of an appropriate IBL based method in integrated STEAM education to increase secondary school students' CT.

Based on the above analysis, this study argues that a more comprehensive curriculum design should ensure students possess essential subject knowledge prior to engaging in IBL activities, while teachers incorporate varied and targeted instructional guidance throughout the learning process. In addition, technological tools, such as 3D printers and AI, can be used to complement inquiry-based teaching. Accordingly, this study proposes an enhanced instructional model that

integrates IBL with the 7E LC model within an integrated STEAM education context, the 7E IBL model, to more effectively promote the development of students' CT.

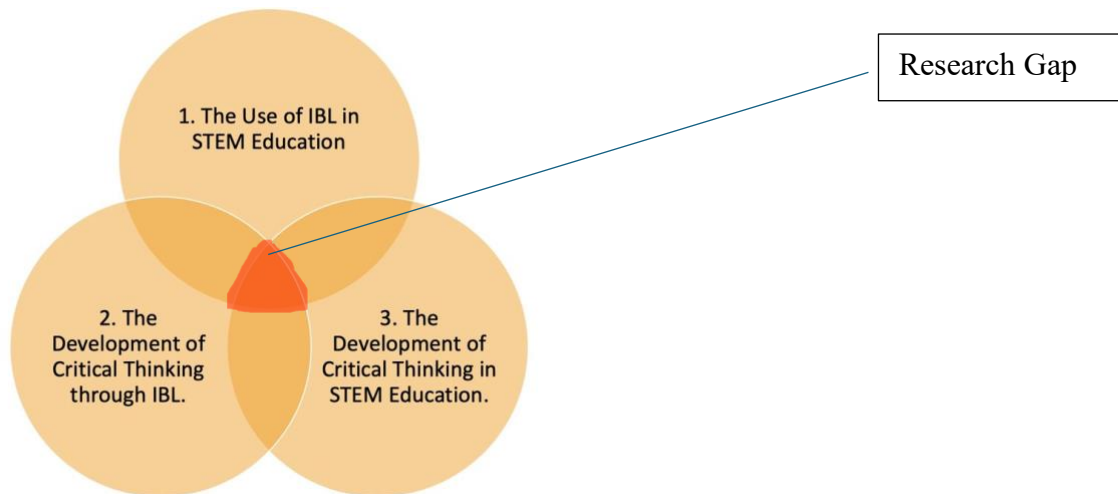


Figure 8: Research gap addressed in this study

4. Methodology, research methods and intervention plan

4.1. Educational experiments

The goal of educational research is to uncover specific forms of knowledge contextualised in educational settings, including the nature of a phenomenon or a complex reality (Keeves, 1990). For conducting educational research, the most widely applied method is the experimental study (Cohen et al., 2002). In education, most experimental studies can help researchers explore ideas and examine relationships between theories and practices (Cohen et al., 2002). Thus, the researcher chose an experimental study for this project, as it permits the identification of relationships between IBL, STEAM education, and the development of CT. The benefits of this research methodology are twofold: firstly, it allows a single control independent variant (the teaching method) in participating schools; secondly, it enables the precise measurement of changes in students' CT skills and dispositions. Meanwhile, Keeves (1990) noted that experimental studies are suitable for testing interventions because they involve changing one factor to examine its impact on another. Using this approach helps researchers get more precise and more accurate results. When applied to this project, the prime inspection point involves examining the changes in students' CT in the control and experimental groups. In this case, students' skills and dispositions are the dependent variables, whereas the relevant independent

variables consist of the teaching method in the school. Therefore, this study must control for unrelated variables between the experimental and control groups and carefully address any concerns related to the intervention design.

Shadish et al. (2002) introduced a way to remove unrelated independent variables. One of the methods is randomisation, which involves randomly selecting and assigning samples so that each participant in the project has an equal opportunity of being assigned to either the experimental or control group. As there is more than one independent variable in each experimental study, in this study, except for 7E IBL in STEAM education, all the other independent variables are unrelated. For example, it could be the impact on students' CT from other subjects (such as mathematics or English literature), the influence of different teaching styles from different teachers, or students' gender. Apart from randomisation, an important reason for selecting this particular school was that every STEAM lesson is co-taught by four participating teachers. This arrangement minimises the potential influence of individual teaching styles on the intervention. Throughout the process, the researchers regularly collected feedback from the teachers and made adjustments to ensure that the 7E IBL model implemented in the experimental group was not introduced into the control group, which was also a key consideration.

4.2. 'True' experiment and quasi-experiment

The design adopted in the participating school is best characterised as a **quasi-experiment**, which imitates many features of an experimental design but does not involve complete random assignment of individuals. As noted in methodological literature, quasi-experimental research "involves the manipulation of an independent variable without random assignment of participants" (Cohen et al., 2002). In educational research, interventions are often delivered to intact classes because using complete randomisation is impractical. Nevertheless, the use of pre-tests, multiple groups, and control of confounding variables can strengthen the validity of such designs (Cook et al., 1979). However, in this study, students were allocated to experimental and control groups by intact classes, without individual random assignment. The design, therefore, corresponds more closely to a "non-equivalent groups design", a common type of quasi-experimental research. Although such a design may have limitations in terms of

internal validity, it offers greater ecological validity and feasibility in real educational contexts, making it a common compromise in school-based intervention studies (Cook et al., 1979).

While quasi-experimental designs face challenges such as potential pre-existing differences between groups, the researcher attempted to mitigate this through careful design and implementation by comparing students' CT levels in the pre-test. Only if students' CTs are at the same level can the project start. The use of pre-tests allowed researchers to evaluate group equivalence, while strict control of teaching variables minimised external influences. Furthermore, by preventing cross-group contamination, the study maintained a reasonable level of internal validity while retaining ecological validity through its implementation in authentic classroom settings.

As highlighted in Table 9, a quasi - experiment needs to fulfil eight preconditions (Cohen et al., 2002); it shows the key features of a quasi-experimental design and its' implication in this study.

Key features of quasi-experimental design	Application in the participating school
1. Presence of control and experimental groups	One control group in grade S2; one in S3.
2. Manipulation of the independent variable	Experimental groups received STEAM lessons based on the 7E IBL model; control groups continued with regular teaching methods
3. No individual random assignment	Students were allocated by intact classes rather than at the individual level. But the classes' allocation in experimental or control group is random.
4. Pre-test to assess baseline differences	All participants completed a pre-test before the intervention
5. Post-test to measure outcomes	All participants completed a post-test to assess changes in CT.
6. Control of confounding variables	Teaching resources, teachers, and curriculum content were kept constant across groups
7. Avoidance of group contamination	Different teaching schedules and group separation reduced potential cross-group influence
8. Multiple control strategies	Pre- and post-testing, group comparisons, and statistical adjustments were applied to enhance validity

Table 9: Key features of a quasi-experiment and their application in this study (Cohen et al., 2002)

4.3. Mixed methods research

Recent research on methodology has demonstrated that although quantitative and qualitative methodology has their own merits, using just a single method always brings inherent limitations (Cohen, 2017). Thus, a more prudent approach is to analyse the project's research questions to determine the most appropriate methods for investigating those questions. Merton and Kendall (1946) advocated a mixed-method approach, suggesting that social science researchers should not be restricted to making a binary choice between collecting either qualitative or quantitative data. Instead, researchers can collect a mixture of both datasets and apply qualitative and quantitative methods according to different needs (Merton & Kendall, 1946). However, this raises the question of when it is appropriate to use one strategy and when to use the other. In this project, the researcher will use different methods according to the characteristics of each research question.

Despite the contrast between quantitative and qualitative methods, both methods have a mutual relationship when it comes to the field of educational research. For this project, a mixed-method approach will be applied to research questions 1 and 2, taking advantage of both qualitative and quantitative data's benefits and providing deeper insight into the research questions. Meanwhile, research question 3 asks: Is there a correlation between CT skills and disposition? The proposed hypothesis is that the higher a student's CT disposition score, the greater the student will gain CT skills. Thus, the researcher will use quantitative data analysis, specifically relevance analysis, to answer this question. The correlation analysis can examine the data from all participating students to assess the relationship between CT skills and dispositions.

In a quantitative approach, the primary benefit resides in the ability to analyse and gather data relating to the quantity of a phenomenon; thus, the quantitative data can be incorporated into an objective analysis which can be extrapolated to view the bigger picture (Chen, 2000). For participant school, quantitative data will be gathered through tests and questionnaires. Therefore, students' CT skills and dispositions can be measured using the most appropriate quantitative tools, with data being collated and analysed to determine the impact of changes in teaching methods. However, this approach also has inherent limitations, as more than quantitative data is needed to understand the nuances of a particular phenomenon (Chen, 2000).

Therefore, it is pivotal to take a pluralistic approach to integrated research by integrating qualitative methods. Classroom observation and one-to-one interviews to collect qualitative data will also be used to find student performance changes. For example, to record the number of questions students raised and whether the questions used CT in two groups and then compare it. Using qualitative methods can add depth to the findings of quantitative data (Chen, 2000). For example, data collection also includes students' self-assessment of their CT skills throughout the learning process and teachers' feedback on students learning.

Overall, an experimental study with a mixed-method research approach will be most appropriate for this study's methodology and research objectives. Furthermore, this approach not only allows for quantitative methods to concentrate on the investigation's findings (such as before and after data comparisons of students' CT), but qualitative research also provides a descriptive analysis which allows for investigation of details surrounding the changes in students' CT.

4.4. Research methods

4.4.1. Methods in educational research

Since the 1880s, the field of educational research has developed into a unique discipline in its own right (Keeves, 2004). The unique history of educational research not only means that it derives knowledge and techniques from other disciplines but also requires guidance from acquiring and propagating knowledge. In addition, social activities contribute to societal changes by shaping individuals' minds through education. Additionally, social activities help to influence society by educating people and moulding their thinking. When combined, these elements distinguish educational research from other disciplines and contribute to the discipline's rise in prominence in the 20th century (Keeves, 2004). This surge in attention resulted from a realisation that education could enormously impact all aspects of social, economic, and political life. Consequently, scholars in this field began to apply different methodologies to the inquiry process of educational research (Cohen et al., 2002). The following section will describe several research methods employed in this project and justify their high level of applicability and conformity to the research questions.

In general, two principal methodologies were formed during the development of educational research: namely, the scientific and the humanistic approaches. Scientific approaches use qualitative and methodical techniques to interrogate educational phenomena (Keeves, 2004). Typically, these methods include the use of controlled experiments, the gathering and analysis of quantitative data, and the use of statistical methodology. The objectives of the scientific method are identifying causal connections and developing conclusions about educational methods using generalisable results (Creswell, 2014). Humanistic educational methods, on the other hand, place a strong emphasis on people's experiences, viewpoints, and subjectivity (Keeves, 2004). In educational contexts, they give priority to comprehension, empathy, and the pursuit of meaning, which are frequently employed qualitative methods include narrative inquiry, interviews, and observation. When combined, scientific and humanistic approaches can assist in answering important problems in the area and offer a more complete picture of educational phenomena. The choice of methods may be influenced by the research question, the subject population, and the resources available to researchers (Neuman, 2014).

In this project, the nature of both research questions is to examine two particular pedagogical phenomena: firstly, the effect of the 7E IBL method on the development of students' CT skills in STEAM education; secondly, the impact on students' CT dispositions. As previously discussed, this study will primarily use mixed methods with quantitative and qualitative research methodology, thus, combining scientific and humanistic approaches to data collection. This is because CT cannot be stranded only by numbers but also by learners' behaviours and teachers' feedback (Bowell et al., 2020). Data will be gathered using both paper and online tests from students in two groups. As Cohen et al. (2017) argued, using tests for data collection allows researchers to receive a robust data set, as well-designed test questions can bring in high-quality numerical data. Simultaneously, the data from tests can be used to conclude specific educational phenomena in people or groups and to assess the effectiveness of intervention projects in education. For instance, in this project, comparing pre- and post-test results will be part of measuring the changes in learners' CT skills and dispositions. If the result shows that the changes in average scores in the experimental group are greater than in the control group, then the intervention of the 7E IBL mode is successful.

4.4.2. Selection of Research context: Hong Kong

In addition to having a somewhat well-established educational system, Hong Kong, an economically developed city, also exhibits a considerable emphasis on and support for STEAM education from the local government, as was covered in the policy analysis section. All of these elements make it an appropriate site for this research. It is important to note that STEAM education is often required for all students in Hong Kong's public secondary schools, which offers a large participant base for the study and successfully guarantees a significant sample size. The researcher also took into account schools in quickly growing mainland cities like Shanghai and Chongqing during the first round of the study. However, investigations revealed that STEAM education in these cities remains predominantly implemented within private schools, often as elective courses. Furthermore, it typically manifests as the integration of interdisciplinary concepts into a single subject (for example, one Chongqing school incorporates STEAM elements into chemistry lessons), rather than as fully independent, comprehensive STEAM curricula. This model diverges from the integrated STEAM education approach sought by this study. In addition, STEAM classes under an elective system often gather students from different classes and academic backgrounds, posing significant challenges for controlling single variables.

In contrast, Hong Kong's public schools predominantly employ a fixed-class system in lower secondary years, where students' course selections are relatively consistent. This provides favourable conditions for variable control in experimental design. Hong Kong's secondary schools also demonstrate certain advantages in STEAM teacher development, as participating teachers reported regularly attending STEAM teaching training organised by their schools or the Education Bureau. Such sustained professional development mechanisms support the stability of teaching quality. Based on these multifaceted considerations, including the mandatory nature of curriculum implementation, the integrated approach to teaching delivery, the accessibility of samples, the controllability of variables, and the professional development mechanisms for teaching staffs, this study ultimately selected Hong Kong as its research context.

4.4.3. Selection of tests

As Cohen et al. (2017) mentioned, before tests can be conducted, a few steps must be taken to maximise the test's effectiveness. First, knowing what is being measured. This project aims to test the CT skills of secondary school students based on seven metrics: Analysis, Inference, Evaluation, Explanation, Induction, Deduction, Numeracy, and Interpretation. And CT disposition includes Truth-seeking, Open-mindedness, Analyticity (foresight), Systematicity (focus), Confidence in Reasoning, Curiosity, and Cognitive Maturity. The definition for each metric showed in Table 10 and Table 11. Second, the researcher needs to ensure whether the result will be referenced. A norm-referenced test means that a student's performance is scored based on the average performance of all students. This project determines the outcome by the percentage of correct answers without parameters. Third, it should clarify if the test questions are from a commercial provider or created by the researcher. The test questions in this project come from Education Insight, CT skills for grades 9-12 and Critical Thinking Disposition Inventory – Chinese Version (CTDI-CV) from Peng et al. (2004). It is the best option the researcher selects among all the test questions available on the market. The specific reasons for this can be found in the following section. Fourth, Are the test scores from the pre-test and post-test? Yes, all test data came from the pre-test or post-test in the educational experiment, depending on the participants' STEAM education schedule. Fifth. Is it group testing or individual testing? After gaining ethical approval from the University of Glasgow and signed consent forms from teachers, students and their parents or guardians, the researchers chose individual testing for the convenience of individual performance in the experiment. This aims to provide opportunities for more data and findings for the subsequent study results. For example, an individual test would influence students' CT skills from gender or age (although it's not the focus in this study). Finally, be careful if participants have permission to participate in the test report. Students in participant school will not be able to be involved or receive the test results after the pre-test because the pre-test and post-test use the same set of questions. So, these will be kept separate to avoid invalidating the post-test data caused by students intentionally training some questions during the experiment. After completing the post-test, the researcher will provide the students with the data.

	Each metric:	Definitions
1	Overall CTS	Continuous application of CT to make well-founded decisions
2	Analysis	The exact diagnosis of the issue and the parts that are crucial for making decisions
3	Interpretation	Finding and defining meanings and context-specific relevance
4	Inference	Deriving logical findings from reasoning and proof
5	Evaluation	Evaluating the veracity of assertions and the persuasiveness of arguments
6	Explanation	Providing the supporting data, arguments, hypotheses, or justifications for conclusions and choices
7	Induction	Considered judgement in complex, dangerous, and unknown situations
8	Deduction	Inferential judgement based on logic in settings that are clearly specified and demanding
9	Numeracy	Consistent use of CTS in numerical circumstances (quantitative reasoning)

Table 10: Definitions of each component of critical thinking skills (Facione, 1990)

	Each metric:	Definitions
1	Truth-seeking	Tenacity to pursue reasons and facts wherever they may point
2	Open-mindedness	Determination to take into account a range of diverse viewpoints
3	Analyticity (Foresight)	persistent endeavour to predict outcomes
4	Systematicity (Focus)	The habit of approaching issues in a systematic and methodical manner
5	Confidence in Reasoning	Constrained relying on the sound discretion
6	Curiosity	Constant focus on learning and a willingness to do so
7	Cognitive Maturity	The expectation that decisions will be made promptly and carefully

Table 11: The definitions of each component of critical thinking disposition (Facione, 1990; Peng et al., 2004)

Test Name	Author	Duration	Language
California Critical Thinking Skills Test (CCTST)	Peter Facione, 1990	45 – 50 minutes	English/ Chinese
California Critical Thinking Disposition Inventory (CCTDI)	Peter Facione, 1990 & 2000 (CCTDI scoring supplement)	45 – 50 minutes	English/ Chinese
Watson-Glaser Critical Thinking Appraisal	Goodwin Watson Edward M.Glaser, 1981	35 – 40 minutes	English, French, German, and Spanish
Cornell Critical Thinking Test, Level Z	Robert Ennis, Jason Millman, 1985	52 questions 50 minutes	English
Halpern Critical Thinking Assessment	Diane F. Halpern, 2013	40 – 60 minutes	English

Table 12: Four main types of multiple-choice tests

There are two main types of CT skills tests in the market: multiple-choice and open-ended. In this study, the researcher will use multiple-choice tests for students, as it benefits the data analysis process when using the quantitative data analysis, while there are also qualitative data from teacher interviews. The mainstream tools for multiple-choice tests are shown in Table 12. of the above mainstream tools, CCTST and CCTDI are the most widely used surveys to test students' CT with explicit instruction (Fawkes et al., 2005). Meanwhile, the CCTST and CCTDI have tested similar aspects of CT skills with their definition mentioned before and could test both the skills and disposition. According to Facione (1990), the original tests for these two are for students who are native English speakers. Chinese scholars have highlighted that when giving Chinese students English version tests, the results showed an unsatisfactory confidence level, although students have strong reading, writing and communication abilities in the English language (Peng et al., 2004).

Given that the CCTDI was developed within a Western sociocultural context, a mere semantic translation into Chinese may overlook the adaptation to behavioural and cultural contexts. Therefore, in the Chinese context, it is necessary to adopt strategies of conceptual equivalence and localisation in order to enhance the validity and fairness of the measurement (Hou, 2022; Peng et al., 2004; Ye, 2003). In order to use the Chinese version test for students in China, the researcher found three types of CT tests on the market: Educate Insight: K12 School Assessment, and Critical Thinking Disposition Inventory, CTDI-CV (based on CCTST and CCTDI), HEIghten Critical Thinking Assessment from ETC (2015) and Critical Thinking Test-Level I by Ye (2003). After comparing the test subjects, the definitions of CT skills, and the accessibility of the test questions, the researchers chose Educate Insight CTS K12: for grades 9-12 to test students' CT skills and CTDI-CV for CT dispositions.

Peng et al. (2004) have translated and updated the disposition questionnaires from the original English version to the Chinese version, the CTDI-CV, details of the questionnaire can be found in

Appendix. They also tested its comprehensibility and reliability by focus group (45 Chinese students) and surveys (1749 students), the results displayed highly acceptable internal consistency and content validity. Thus, the CTDI-CV could efficiently test Chinese students' CT dispositions (Peng et al., 2004). Similarly, an educational company from the US, Insight

Assessment, has a Chinese version of CCTST called Educate Insight: K12 School Assessment. It also showed positive performance on the tests' validity and reliability.

4.5. Intervention plan in participating school

4.5.1. Plan introduction

Experimental Group	Control Group
STEAM education with 7E IBL model	STEAM education with standard learning techniques (the PBL)

Table 13: Details of the experimental and control groups in participating school.

	February 2023	June 2023
Experimental Group: (S2 and S3, aged 13-15 years) CT Skills: 87 CT Dispositions:121	Pre-test	Post-test
Control Group (S2 and S3, aged 13-15 years) CT Skills: 75 CT Dispositions:119	Pre-test	Post-test

Table 14: The final plan: Timeline for pre-test and post-test in participating school.

The participating school is located in Hong Kong, with 162 participants aged 13-14 years being recruited for CT skills. As shown in Table 13 and Table 14, for CT skills, group one (75 students) will be the control group receiving standard STEAM teaching methods, which is project-based learning. Group two (87 students) will form an experimental group receiving STEAM teaching under the 7E IBL model. As for research that test the CT dispositions, 240 students were recruited; 121 were in the experimental group, and 119 were in the control group. Similarly, the experimental group will receive the 7E IBL model as an intervention to the curriculum of every STEAM education lesson. In comparing groups 1 and 2, the aim is to assess to what extent STEAM education with 7E IBL model may influence students' CT skills and dispositions. As shown in Table 14, an intervention study with pre - and post-tests is scheduled for semester two (February to June 2023). The pre-test will finish in February, and the post-test will commence in June 2023. Research questions will also be answered using interviews with participating teachers. The results of this experiment will be calculated by subtracting the difference in results obtained between the post-test data set of the experimental and control

groups from the pre-test data set to obtain a value for the change in students' CT skills and dispositions (the variables).

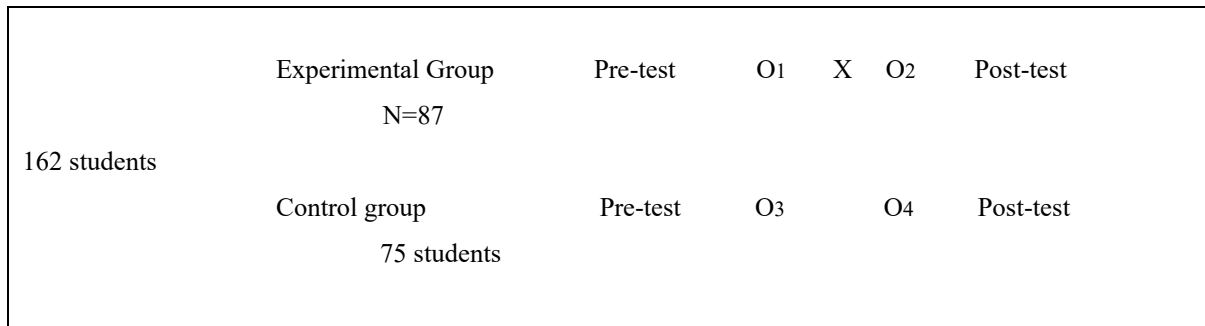


Figure 9: Distribution methods example for groups in CT skills

All participating students will receive 90 minutes of STEAM class every two weeks. As shown in Figure 9, all students will be pre-tested at the beginning of semester two before their STEAM education classes commence. O1 and O3 are the starting levels in the students' CT skills and dispositions test results and X represents the moment of experimental intervention. Students' CT skills and dispositions levels will be tested again at the end of semester. Points O2 and O4 represent their CT skills and dispositions levels after one semester of study. During the study, opportunities may arise to advise participating teachers as to whether they would benefit from adjusting their methods to enhance the effectiveness of their STEAM teaching in the future. Details of this will be introduced in Chapter 5. The implementation of the 7E IBL model in participant school.

4.5.2. Timeline and operating process

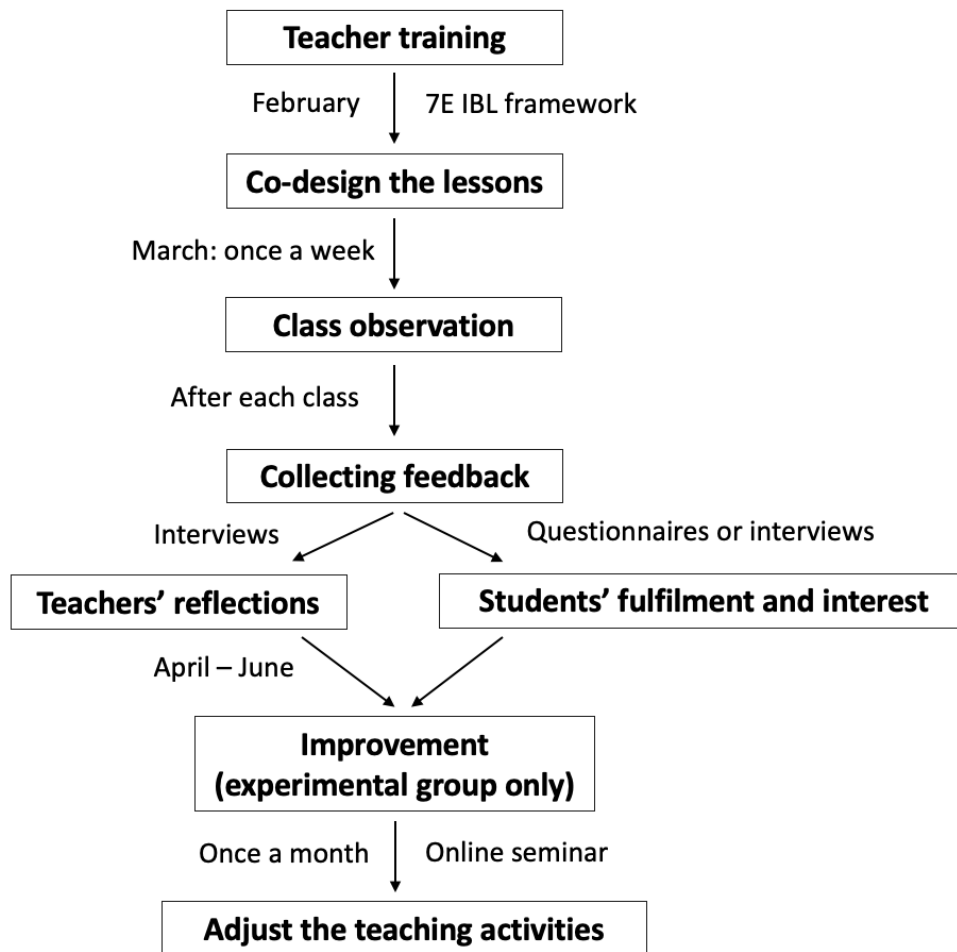


Figure 10: Timeline and instruction for the intervention plan

As shown in Figure 10, the intervention study scheduled to take place at the participant's school in Hong Kong is set to run from February to July 2023. Students sorted into the experimental group will participate in fourteen STEAM education lessons utilising the 7E IBL teaching method through in semester two. In the control group, students will receive the same amount teaching activities through a project-based learning method as they are used to. More details on the comparison before and after adopting the intervention plan could be find in 5.3.2. Differences between the 7E LC model, the IBL method and the 7E IBL model (the new model), and the differences after implementations in class.

This project will commence with the researcher training teachers at the participating school in February 2023, via one or two 1/2-hour workshops. PowerPoint slides for this workshop can

be found in the appendix. The workshop comprises five sections: (1) An introduction to the project and the 7E IBL model. (2) 15 minutes consisting of an experiment and feedback. This section is where the researcher assumes the role of a STEAM educator, demonstrating to teachers how to lead a lesson based on the 7E IBL model (details can be found in the following sections). (3) Ten minutes scheduled solely for interactions. The goal of this portion of the training is for teachers to collaboratively design a lesson using the method they have just been introduced to. (4) A presentation will be conducted after completing their lesson plan. Teachers will present their lesson plans and answer any questions that may arise. (5) Finally, the workshop will close with an open discussion on the advantages and disadvantages of this process.

Before classes, the researcher will collect lesson designs (in PowerPoint format) from teachers before their classes begin to ensure that each step follows the intervention plan. The researcher will seek evidence of following the 7E IBL model discussed. This will apply only to the experimental group for the duration of the experiment. To gauge the quality of teaching, feedback will be collected from both teachers and students following each lesson to identify potential areas for improvement. In the control group, the researcher will also collect feedback and reflections from teachers and students but will not adjust for improvement to safeguard the validity of the control group by maintaining all interventions unchanged. The feedback from the teachers will be collected through short interviews, while short questionnaires will be randomly issued to five students to collect data from both groups. From April to July, an online seminar concerning STEAM education will be available to researchers and educators in the experimental group each month if needed. It is an opportunity for those involved to give feedback on their lessons and learn from the experiences of others. Additionally, one of the primary ways is to collect teachers' teaching PowerPoint Slides, which collect information regarding the project's progress and further acquisition. Below Table 15 and Table 16 shown the context of STEAM education in semester 2 in participant school as an example.

Product	Lesson	content
S2 3D Printing	1-2	<ul style="list-style-type: none"> • Introduction of 3D Printing • Use of TinkerCad to make keychain
	3-4	<ul style="list-style-type: none"> • Introduction of design thinking • Design of McQueen car device by students
	5-6	<ul style="list-style-type: none"> • Design and drawing by students
	7-8	<ul style="list-style-type: none"> • Design and drawing by students • 3D print
	9-10	<ul style="list-style-type: none"> • Introduction of 3D printer • Introduction of Ultimaker • Refine keychain Design (+one more function)
	11-12	<ul style="list-style-type: none"> • Transcript students' drawing to product • (Presentation)
	13-14	<ul style="list-style-type: none"> • Presentation

Table 15: S2 STEAM education curriculum content in participant school

Product	Lesson	content
S3 Laser Cut	1-2	<ul style="list-style-type: none"> • Introduction of Laser cut • Product of using Laser cut • Software of using Laser cut
	3-4	<ul style="list-style-type: none"> • Making a simple product using laser cut
	5-6	<ul style="list-style-type: none"> • Advance technique on drawing laser cut diagram • How to work with the laser cutter?
	7-8	<ul style="list-style-type: none"> • Product of using Laser cut
	9-10	<ul style="list-style-type: none"> • Design and drawing by students
	11-12	<ul style="list-style-type: none"> • Design and drawing by students
	13-14	<ul style="list-style-type: none"> • Transcript students' drawing to product • Presentation

Table 16: S3 STEAM education curriculum content in participant school.

4.6. Quantitative and qualitative data analysis

4.6.1. Data collected

In this project, six types of data were collected from the pre-test, as shown in Table 17 and Table 18. The researcher is using online tests and paper questionnaires to collect quantitative data on the impact of 7E IBL model in STEAM education on students' CT skills (162 participants) and CT dispositions (240 participants) by using Educate Insight: grade 9-12 and CTDI-CV; In addition, interviews were utilised to gather further qualitative data relevant to the research topic.

1. Online CT skills test: 162
2. Paper questionnaires for CT dispositions: 240
3. Interviews for teachers on the use of 7E IBL model: 5 interviews during intervention and 4 final interviews
4. Interviews for students on the feedback of STEAM education after each class: 5 students
5. Case study for virtual data, including photos and video of teaching activities
6. Teachers' PowerPoint Slides during teaching activities

Table 17: Data collected from pre-test in participant school.

	CT dispositions	CT skills	Research question3
Experimental Group	121	87	N=88
Control Group	119	75	
Total	240	162	

Table 18: Numbers of pre-test participants for each group

4.6.2. Data cleaning process

This study employed the CT tests and CT disposition questionnaires, which have been widely used both in China and internationally. The instrument has already demonstrated satisfactory reliability and validity in previous research; therefore, additional tests of reliability and validity were not repeated in this study (Facione et al., 2000; Peng et al., 2004). However, this project applies strict data-cleaning criteria to maintain the quality of the data collected, as the researcher placed greater value on reliability than on maximising sample size. The transparency and rigour of the data-cleaning process, therefore, strengthen the credibility of the findings. Questionnaires and tests that fail the data-cleaning process will be archived for documentation purposes and omitted from the subsequent analysis.

Table 19 illustrates the data-cleaning criteria for the CT skills test, where incomplete tests and those completed in an unusually short time were removed. According to pilot testing, it usually takes 20–35 minutes for a secondary school student to complete the test; thus, responses completed in under 20 minutes were considered unreliable and excluded. In addition, only fully completed tests were retained, with those not reaching a completion rate of 1.0 also removed. The results for the validated number of CT skills tests, which will be analysed later, can be found in Table 20.

Review	Criteria	Inclusion
Time	≥ 20 minutes	Yes
	< 20 minutes	No
Completion	$= 1.0$	Yes
	< 1.0	No

Table 19: Data cleaning rules for CT skills.

	N experimental group	N control group
Pre-test	53	66
Post-test	26	27

Table 20: Final numbers of CT skills test

As shown in Table 20, the number of post-tests completed for the CT skills assessment decreased by nearly half, a pattern that did not occur in the collection of CT disposition questionnaires. The reasons may be partly attributable to the fact that the CT skills tests were completed after school without teacher supervision. Additionally, students may have perceived, based on their experience with the pre-test, that the CT skills assessment was more demanding than the CT disposition questionnaire. As the CT skills assessment was low-stakes and cognitively demanding, students likely lacked the intrinsic motivation to engage with the complex problem-solving required in the second round. Bridgid (2015) note that in low stakes testing environments, where results have no direct consequence on a student's grades, examinee effort frequently declines, particularly when the tasks are perceived as difficult or lengthy. Although such non-random attrition can threaten internal validity (Shadish et al., 2002), it is worth noting that this project utilised a mixed-methods design. Researchers were able to extract qualitative data regarding changes in students' CT skills from the teachers' perspective, thereby triangulating and supporting the quantitative results and ensuring the findings remain robust. Specific recommendations to address participant attrition in future iterations can be found in the Limitations chapter.

As CT dispositions used a scaled questionnaire, the data-cleaning process required more complex methods. For example, a *consistency check* was applied to test whether participants'

responses were logical between items. This helped identify and remove invalid questionnaires, such as those completed carelessly or with contradictory answers. Consistency-based screening has been widely used in survey research to flag responses that are inconsistent, extreme, or otherwise unreliable (Curran, 2016; Huang et al., 2012). In addition, *validity check items* within the questionnaire were used. For instance, in the section measuring analytical ability, one item asked, "I can be considered a logical person, " while another stated, "I am not a logical person but often pretend to be. " If a respondent strongly agreed with both statements, it indicated a lack of attention to the questions. *Response pattern analysis* was also considered: answer sheets showing too many contradictions or extreme choices (such as marking "strongly agree" for every item) were excluded.

In practice, this project followed the above three main principles when screening questionnaires. First, rules were set in advance to pair certain items that should theoretically show positive or negative correlations, producing nine such rules in total as shown in Table 21. Each questionnaire was checked against these rules. Obvious outliers, for example, all questions are 6 (on a six-point scale ranging from 1 = strongly disagree to 6 = strongly agree) or those using only one or two response options (all 2 or 3 as answers), were immediately removed as inattentive cases. For the remaining data, a 30% threshold was applied: if four or more responses violated the predefined logical rules, the questionnaire was considered inconsistent and excluded as invalid. Following recommendations from previous studies on careless response detection, a 30% threshold was set to balance the risk of retaining inconsistent responses with the need to preserve sufficient sample size (Huang et al., 2012; Meade & Craig, 2012). In this study, violating four or more out of nine logical rules was considered strong evidence of inconsistency, warranting exclusion of the questionnaire. This rule-based consistency method has been widely adopted in questionnaire research to detect contradictory, extreme, or careless responses (Huang et al., 2012; Meade & Craig, 2012).

Item A	Item B	Relation	Note (normally)
B6	B8	Similar	
B3	B6(8)	Opposite	
C5	C8	Opposite	If C8 high, C5 low
D3	A4	Opposite	
D8	D9	Opposite	Might be
E4	E6	Similar	
E4	D8	Opposite	
F8	F9	Similar	If F8 high, F9 high
G10 normally low			

Table 21: Questionnaire pairing rules

	N experimental group	N control group
Pre-test	90	88
Post-test	63	42

Table 22: Final numbers of CT dispositions

• A (Truth-seeking)
• B (Open-mindedness)
• C (Analyticity)
• D (Systematicity)
• E (Confidence in Reasoning)
• F (Curiosity)
• G (Cognitive Maturity)
3-8: question number

4.6.3. Quantitative data analysis plan

In educational research, a sound understanding of statistical methods is fundamental to producing valid and reliable findings. In this study, SPSS will be used as the main tool for data handling and analysis. The software is widely applied in the social sciences and is particularly appropriate for educational research because of its flexibility and range of analytical functions. After data on students' CT dispositions and skills have been collected, the raw dataset will be cleaned to remove inconsistencies and errors, allowing for a clearer interpretation of the results. Pre- and post-test responses will then be converted into numerical scores and analysed using independent and paired-sample t-tests in SPSS. The programme will also be employed to organise the data into tables and produce statistical graphs to support interpretation. The next section outlines the plan for analysing the quantitative data from the pre-test.

For research questions one and two, which tested the changes in students' CT skills and disposition, the focus was on comparing mean scores between groups (experimental vs. control), without collecting paired pre- and post-test data at the individual level. The data sets two independent samples with sufficient size ($n > 30$) that meet the assumption of normal distribution. In such cases, independent-samples t -tests are considered appropriate for examining group mean differences. Therefore, independent t -tests were used to compare CT dispositions and skills between groups. When statistically significant differences were showed, effect sizes will be calculated using Cohen's d , following conventional practice in behavioural and educational research (Cohen, 2013; Valentine & Cooper, 2003). In line with widely accepted guidelines, a Cohen's d of around 0.5 was interpreted as a moderate effect, values above 0.5 as strong, and values below 0.5 as small effects with less practical importance (Lakens, 2013). Research question three investigated the relationship between CT skills and dispositions. After data cleaning, valid responses from 88 students were retained. Pearson's correlation coefficient was used to examine associations, and scatterplots were generated to visualise the data pattern (Field, 2024).

4.6.4. Qualitative data analysis plan

Table 17 displays that the qualitative data used in this project consisted of teacher interviews, lesson plans, and visual materials collected during teaching activities. Thus far, the researcher has collected qualitative data from four teachers, as well as visual materials, such as photographs taken during lessons. Firstly, the interviews with STEAM education teachers were conducted in a semi-structured format. This allows teachers to lead the discussions in a conversational format without being too unguided and causing the interviewees to stray from the topic or be too free with the content of the conversation, which would make the data analysis too challenging (Arksey & Knight, 1999). The researcher translated the discussions into specific interview questions based on the research needs which can be found in

Appendix. Once the general direction was set up, during the interviews, the teachers were asked to share their experiences and feelings about using the 7E IBL model, as well as evaluate the students' performance in CT. The advantage is that the interview questions are flexible, regarding how and in what order they are asked, how the interviewees respond, and when and where the interview takes place (Arksey & Knight, 1999). Sometimes interviewees can take the lead in the interview and give more information, and sometimes the interviewer improvises according to her judgement and takes the lead in digging deeper into the valuable points

(Arksey & Knight, 1999). The researcher will use a thematic analysis approach to analyse the data from the teacher interviews. As shown in Figure 11 below, this involves converting the recorded interviews into text, generating codes through MAXQDA, reviewing the data, and distilling themes to ensure that all relevant data is coded and all themes are defined and named coherently and clearly (Braun & Clarke, 2006; Maguire & Delahunt, 2017). Finally, the findings will be presented in a structured manner.

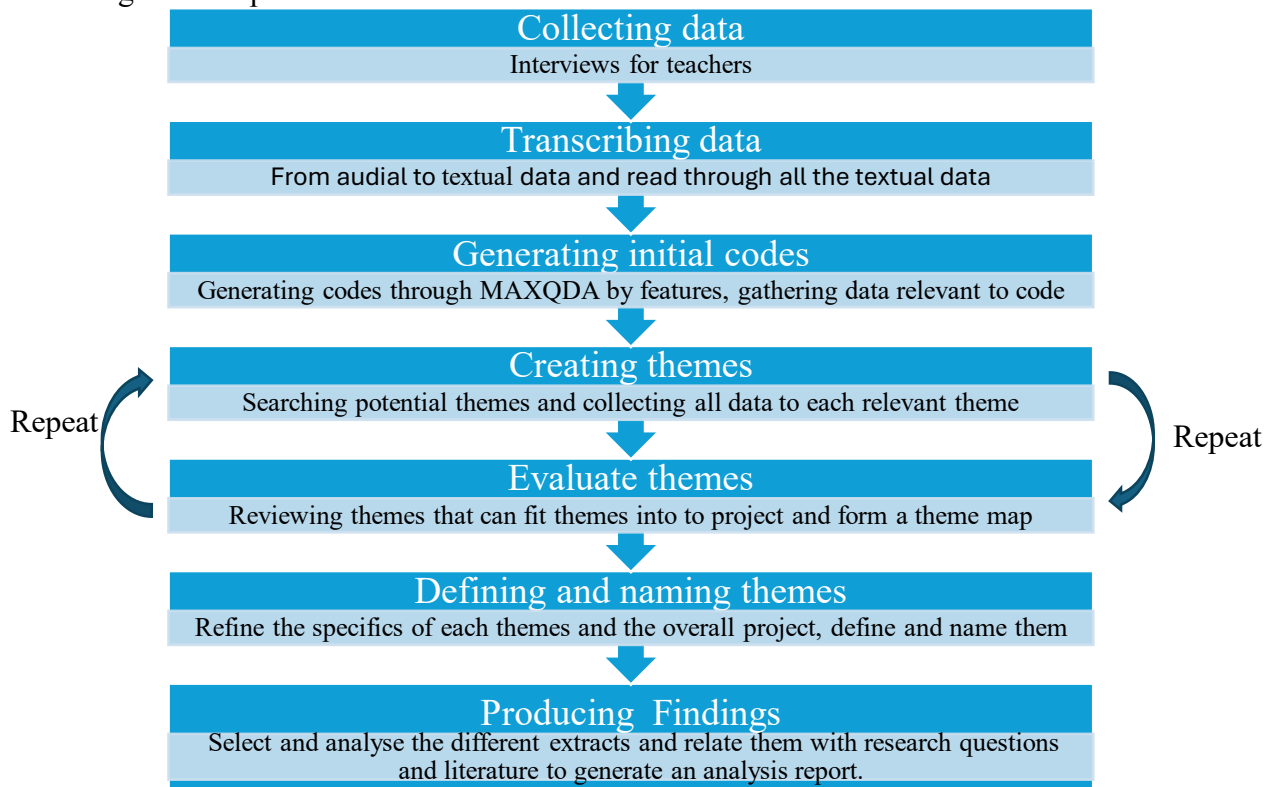


Figure 11: The process of thematic analysis (Braun and Clarke, 2006; Maguire and Delahunt, 2017).

4.7.1. Trustworthiness

Identify the relationship between researcher and participants and build a genuine relationship.

To establish a sincere relationship with the participants and enhance the internal credibility of the data source, it is crucial to reflect on the data-gathering method. The researcher provided each participant with an explanation of the research goal at the outset of my data collection to help them avoid the potential bias that can occur when a researcher approaches participants in a somewhat top-down manner. The researcher described herself as a PhD candidate who had comparable educational and professional experiences to theirs. Also reassured them that their colleagues and school administrators would not have access to the data and explained that it would all be kept completely private. Along with this verbal guarantee, the researcher also tried

to close any apparent gap between them. These initiatives made it possible for the data to be gathered in a welcoming and constructive setting.

A variety of data gathering techniques

To increase its credibility, this study used a variety of data collection techniques. The main techniques for gathering data were questionnaires, interviews, tests, and document analysis. Before interviewing each teacher, this study purposefully planned observations. As a result, the teachers' perspectives were reflected in the useful scenarios that were discussed during the interviews based on the observations.

Member check

A member check is a meaningful tactic to improve the reliability, confirmability, and external credibility of research. Three levels of member checks were included in this study. First, the study methodology was examined through a member check with researcher' supervisors and the principal of the school before any data was collected. It is important to note that the school principal was not involved in this study. Second, some of the data transcriptions were returned to a STEAM education teachers for peer assessment following data collection. However, only some of the transcriptions were subjected to peer review because of time restrictions and teacher availability. Finally, to further improve confirmability, the researcher shared the coding results with supervisors for input after finishing a draft of the coding (around the axial coding stage) for one participating teacher.

4.7.2. Research ethics

After receiving ethical approval from the University of Glasgow, the study was carried out. Furthermore, because the study involved children under the age of 18, three sets of consent forms were distributed to the principal of the secondary school, the participating teachers, and the parents and students of the participating classes. Parents received the consent form via the participating instructors. Prior to their involvement, all participants and their schools were aware of the study's goal and methodology. Every participant gave their consent to participate in this study, and they were made aware of their freedom to leave at any moment. With the consent of the participants, all visual and auditory data, including images, videos, and audio

recordings, were collected. No images or videos that feature the students' faces directly were captured. One crucial ethical research principle is confidentiality. Only the researcher knew all of the information gathered in order to maintain the confidentiality of the records. The transcripts and final reports omitted any names of the informants and schools that could reveal the identity of the informants.

5. The implementation of the 7E IBL model in participant school

5.1. The first draft of the 7E IBL model

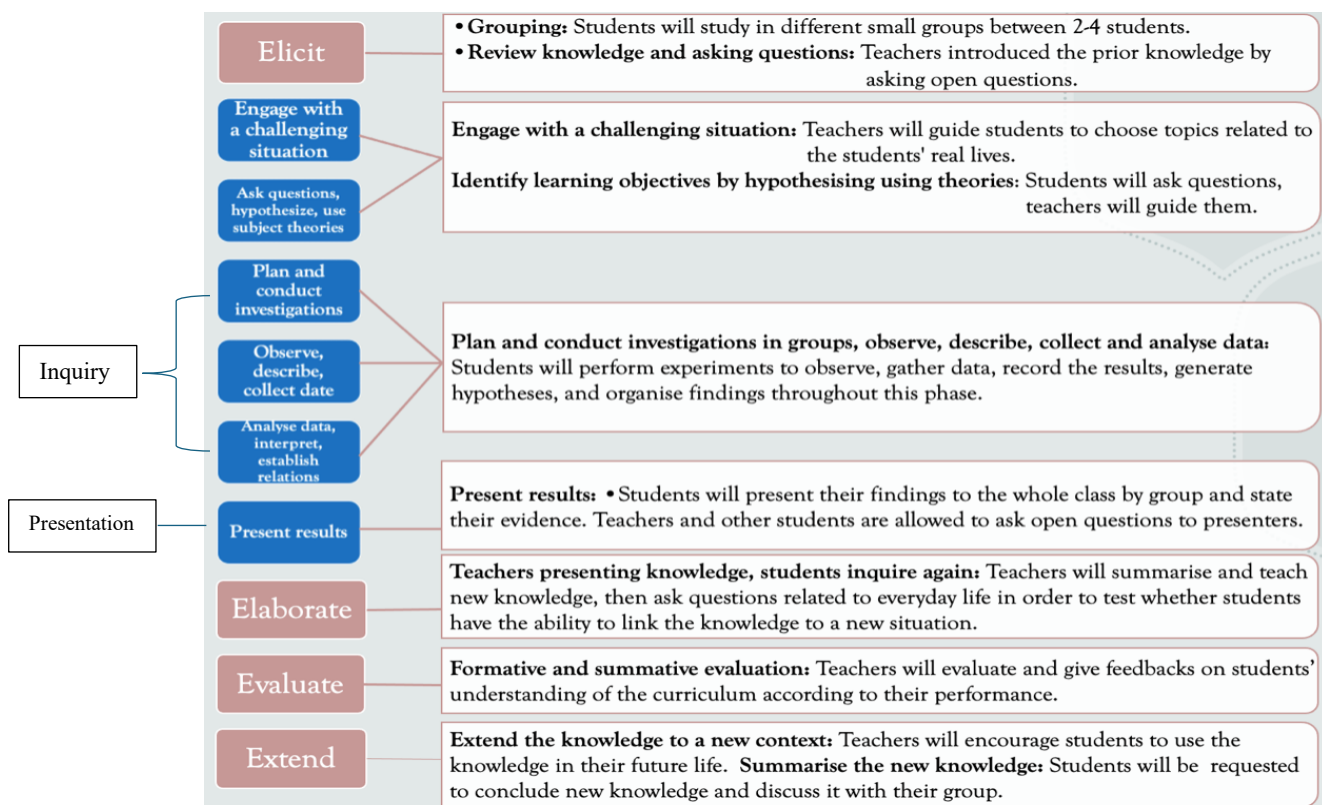


Figure 12: The first draft of the 7E IBL model according to 7E LC model and IBL

5.2. Challenges from implementation and adaptations needed

When implementing the first version of the new model, according to teachers' feedback, three key challenges arose. Firstly, the interviews with teachers demonstrate that time is an issue. Secondly, all the teachers believed there were too many steps to follow up after the implementation, and that they potentially lacked suitability for education. Thirdly, it was

discovered that teachers' and students' attitudes towards STEAM education differ from those held toward the subjects tested in the College Entrance Examination (CEE) (more details on this will be discussed at the 'Notebook' section below). In this way, both teachers and students shared that they hoped for the STEAM education course to be a more manageable low-pressure subject, where the content was covered in the classroom rather than after school. Hence, based on these initial findings, the first version of the model was edited to make it more suitable for classroom teaching. The details surrounding the new model and the reasons for change are shared below.

5.2.1. Elicit

When compared to the IBL method, the new model maintains the 'Elicit' element found in Eisenkraft's 7E LC Model. However, this is enhanced with the addition of teaching new technical skills at the start of each lesson. This is an appropriate addition because eliciting and teaching new skills allows educators to include prior knowledge organically, while also introducing new subject matter briefly (Goodchild et al., 2013). More specifically, the curriculum design for STEAM education in participant school for the entire semester is consistent; in practical terms, the lessons are interconnected with their use of knowledge, and the inquiry activities that take place in the middle of each lesson require specific technological skills to use different software. For instance, in the Year two class, semester two's teaching objective is to design and make a clock using laser cutters. This means that the students need to complete the task by following specific steps, and that each lesson follows on from the previous lesson. Similarly, this means that as the course progresses, students develop their ability in being able to use the new software that controls the laser-cutting machines.

Teacher interviews highlight the importance of reviewing prior knowledge and teaching new technical skills before each lesson. For example, from the teachers' perspective, reviewing prior knowledge can increase their teaching efficiency, thereby enabling them to apply more focus on the curriculum's new knowledge teaching, rather than simply repeating information that students should have known during the inquiry process. More specifically, one of the participating teachers indicated that "students in the experimental group asked fewer questions about the essential subject knowledge they learned in previous lessons, such as a specific technological skill to use software". In terms of the control group, most of the students' questions were about the technical matters they had encountered during their inquiry activities,

and they stated that it took teachers a long time to explain the technical skills that they should have mastered before the lesson. A possible reason for this is that students tend to forget their prior knowledge since the STEAM education course is only conducted every two weeks. It is common for Hong Kong's secondary schools to teach STEAM in either one lesson per week or every two weeks. In contrast, in the experimental group, teachers helped their students to review their prior skills before starting a new lesson. As a result, teachers experienced higher levels of teaching quality by adding the concept of 'Elicit', especially since they had more time to focus on new knowledge in experimental group. More details on students' questions can be found in 7.1. Students' questions during lessons

From students' perspectives, solidifying prior knowledge before each lesson provides an additional stimulus that can support deepening their memory of that part of previous knowledge. This is achieved by reinforcing prior knowledge and subject matter, which serves as a crucial foundation for future learning. Meanwhile, the students could only engage in the practical activities once they had learned new skills specific to using the chosen software. Consequently, the emphasis on engaging with prior learning meant that the students were better equipped to approach learning and explore new knowledge more easily and efficiently in the classroom. Besides, students will have gained stronger connections between existing and new knowledge before the next lesson. In the long term, this approach can support learners' coherence and logical understanding of subject knowledge, culminating in a well-rounded, holistic curriculum knowledge system.

Overall, the proposed new model will ensure that the review of prior knowledge and new technical skills taught at the beginning of each lesson is included. From this, teachers will be able to focus more on improving their efficiency, thereby supporting learners in developing a coherent and logical understanding of subject knowledge; thus, culminating in a well-rounded curriculum knowledge system.

5.2.2. Elaborate

The 'Elaborate' element has moved from a separate step into the process of inquiry activities after students have used specific new knowledge. This allows teachers to save more time and, thus, increase their teaching efficiency. Meanwhile, students can reuse their knowledge when

conducting an exploration, thereby stimulating timely connections and helping them to deepen their memory while understanding and applying their knowledge. Furthermore, some changes have been made to the ‘Elaborate’ section when compared to the 7E LC model. For instance, the elaborate questions in the new model are dependent on the amount of specific subject knowledge learned in one lesson. As such, if a single lesson encompasses three main points of subject matter, then there would be three elaborate questions. Previously, in the 7E IBL model, teachers would only ask their students one big question which embedded all of the taught subject matter in that lesson. Moreover, unlike the 7E LC model, the 7E IBL model’s Elaborate section requires students to not only make a plan to answer these questions, but they will also need to finish the practical element at least once after producing the plan. For example, under the 7E LC model, the elaborate element could have led the teacher to ask the whole class to: ‘How to create a plan to design a photo frame after you have made a clock surface with the laser cutting machine?’ On the contrary, under the new model, it will require the Elaborate questions to be separated into ‘mini tasks’ that are dependent on the key point of scientific knowledge in that lesson. Likewise, the timing of asking these questions depends on the students’ inquiry process of each group, since teachers will observe each group and ask them the question as soon as they finish a mini task. In this situation, an elaborate question could include: ‘After you learn how to design a circle on your clock surface using the software, please use your imagination on how to draw another shape on your clock surface?’ The use of mini tasks can save teachers time by enabling each group to move on to the next task when they are ready, rather than waiting for the whole class to finish. In addition, this was put into practice several times and has shown positive results in the experimental group, therefore saving teachers time when asking students elaboration questions directly after each subject matter.

5.2.3. Extension

In the new model, the final session of each lesson no longer uses a single extension, but instead, is a knowledge summary and extension tasks. As shown in *Figure 9*, the first step for this section is for the teachers to summarise the curriculum knowledge in the lesson. The interviews with the teachers highlighted that they would prefer to keep summarising subject knowledge along with extension mini tasks at the end of each lesson. This is because, for example, one teacher found that in the experimental group, when the summary section with all the curriculum knowledge was added, the learners were more attracted and demonstrated high levels of focus on teachers’ speaking about the knowledge summary. This was not only because the students

realised the importance of the subject matter but was also the result of having an extension task as a formative assessment tool for later in the lesson. During this extension activities, students will be able to ask their near-transfer questions, which require using the subject knowledge learned in that lesson. For example, after learning how to use a 3D printer to make a key chain, they can ask themselves what and how they would make another product using a 3D printer. It is important to note here that in the extension, the questions differ from those in the elaborate inquiry stage, even though they are all near-transfer questions. Each question in the elaboration step is designed to use a single skill and comprises several questions according to the number of primary subject matter. In contrast, in the last step, there will be one complex question: Students will reuse all the curriculum knowledge in another real-world scenario, create a plan about how to do it, and then mark it down in the notebook. More details on the notebook can be found in 7.2.4. Notebook in the extension step.

Another reason for designing this session is for teachers to be able to combine a summary of prior learning with the critical points of the previous lesson before moving on to the next lesson. By revisiting and repeating prior learning in the extension, students can strengthen the connection and memory of the key knowledge points. For teachers, this improves the quality of their teaching, engages students and maximises the time available in the classroom for deeper learning and use of subject knowledge. For the students, this reduces the number of questions about what they have learned in the next lesson. However, in the control group, the number of questions on the previous knowledge was double that of those in the experimental group. Meanwhile, students were more relaxed at the end of each lesson without teachers summarising subject knowledge.

5.2.4. Notebook as a learning journal

The use of notebooks corresponds with one of the barriers derived from another article analysing China's STEAM education policy. One such barrier is that students spend less time and energy on STEAM education because it is not examined in the CEE. Therefore, in the schools in Hong Kong that emphasise academic achievement, such as the Band 1 schools that have been recognised as the best level of academic schools by the Government (like the participant school), teachers do not want STEAM education to become a stressful subject, as they need to apply their focus on the examination subjects. From the teachers' interviews, it is

clear that they would prefer for STEAM education to be completed only in the classroom and that no after-school homework should be given to students. However, most of the teachers interviewed shared that they believed that notebooks are valuable tools for students as they can be used to summarise learning and complete extension tasks at the end of each lesson. As such, the original plan to use the notebook as a homework tool was rejected, and instead, they are now used for the last part of the session that takes place in the classroom. In the new model, the role of the notebook is to support students in summarising the session's key points and, secondly, to apply their prior learning to other real-world situations, and to record any future plans. This part of the session can involve teamwork, such as collaborating to complete tasks in the notebook, working on a new scenario based on prior learning, and deciding to use it to achieve a successful design or product. There is an example of the notebook in appendix. According to all the changes described above, the final version of the 7E IBL model can be found in Figure 13 below.

5.3. The final version of the 7E IBL model

- **Preparation**
 - a. **Elicit** (grouping): key considerations from informal learning. Review the prior knowledge if needed.
 - b. **Concept and skills introduction**: skills, curriculum terms/software instruction
- **Design**
 - a. **Engage** with a real-world challenging situation and choose a topic by students themselves.
 - b. Plan with a learning objective.
- **Inquiry**
 - a. Conduct **investigations and** exploration in groups, use suitable **technology** for bettering inquiring.
(for example, 3D printer, VR technic, laser cutting, AI, or mobile-based technic)
Allow enough time for peer discussions and interaction with teachers.
 - b. Collect and analyse data.
 - c. **Elaborate**: Teachers' near-transfer questions, reuse knowledge in a different scenario.
- **Presentation**
 - a. Students lead, present inquiry process and findings, explain it.
 - b. Questions and answers
 - c. **Evaluate**, peer and teachers review
- **Extension**
 - a. **Knowledge Summary**: Teacher's summary of the acquired new knowledge
 - b. **Extend**: Questions use near-transfer knowledge, students lead (group discussions), possible use of a **notebook** as a learning journal with mini task to finish in class.

Figure 13: The final version of the 7E IBL model

5.3.1. Aims of the new framework

1. To emphasise students' inquiry-based learning, focusing on self-learning abilities; promoting teamwork and interaction (with peers and teachers)
2. To utilise acquired knowledge through repetitive application, fostering connections and integrating inquiry-based activities for students to master subject knowledge within the constraints of limited classroom time
3. To strengthen the linkage between new and prior knowledge so that students can form a comprehensive and coherent interdisciplinary knowledge framework
4. To focus on cultivating students' higher-order thinking skills, such as CT, encouraging learners to extend their acquired knowledge beyond the classroom and preparing them to become twenty-first-century talents
5. To provide teachers of STEAM education with a template about how to design a lesson to help them improve teaching quality

5.3.2. Differences between the 7E LC model, the IBL method and the 7E IBL model (the new model), and the differences after implementations in class

No.	Steps in teaching activities	7E LC model	IBL method	7E IBL model
1	Review the prior knowledge	✓		✓
2	Concepts and skills introduction			✓
3	Teacher-to-student centred classroom	✓	✓	✓
4	Group study		✓	✓
5	Engage with real-world problem	✓	✓	✓
6	Teacher guided inquiry		✓ Part of	✓
7	Technologies involved inquiry	✓	✓	✓
8	Knowledge/findings conclusion		✓	✓
9	Evaluation by peers and teachers	✓		✓
10	Presentations with Q&A		✓	✓
11	Knowledge transfer	✓ after inquiry		✓ during & after inquiry
12	Teacher summaries subject matters			✓
13	Learning journal			✓
14	Cycle study	✓	✓	✓

Table 23: The differences between 7E LC model, IBL method and the 7E IBL model

Before Intervention (Project-based Learning)	After Intervention (7E IBL)
Individual Study and group study (half half)	Group study only (4-5 students in one group)
Engage: Teachers provide a project and tasks with a specific topic	Engage: Teachers present a topic, and students decide the tasks related to their daily life. Concept and skills introduction at the beginning of the lesson by teachers.
Explore: Teachers provide method for students to solve pre-defined problems.	Explore: Students analyse problems and develop models to find solutions using inquiry and critical thinking.
Inquiry Process: As classroom leader, teachers provide the students with the main subject knowledge. Students do the experiment/inquiry.	Inquiry Process: Students lead, and teachers guide. Teachers are also facilitators who help students by explaining relevant terms and answering appropriate questions when needed.
Explain: Teachers pass new knowledge to their students directly.	Explain: Students' self-concepts connect real-world problems to curriculum theory, helping them to investigate phenomena.
Presentation and Explanation: One presentation at the end of the semester	Presentation and Explanation: Students will present in each class with a Q&A section; they question and communicate with their classmates and teachers. Meanwhile, they will explain their process of identifying and answering questions using relevant evidence.
Elaborate: This does not take place	Elaborate: Teachers guide their students to use their new knowledge in various situations, thus helping them develop transferable skills and knowledge. In this process, further questions are coming from teachers, then students need to find a solution and do it. Meanwhile, it is an opportunity for learners to practice their CT.
Evaluation: Once at the end of the semester during the presentation stage, sometime in the inquiry process, while students communications.	Evaluation: The evaluation will be applied during presentation Q&A section. Students have opportunities to raise questions to the presenters.
Extend: This does not take place	Extend: Teachers will summarise the curriculum knowledge learned in that class firstly. Then teachers guide students to ask a new near transfer question as a mini task in a new life situation, find a solution, and make a plan. This section will add at the end of each lesson with a notebook to write down. In this process, the students will complete the transformation of knowledge and practice their CT.

Table 24: Differences from PBL method that participant school used and the 7E IBL model.

As indicated in Table 24, although the control group followed a traditional STEM curriculum structure, the instructional approach adopted was Project-Based Learning. PBL, by definition,

is grounded in authentic problem-solving in projects and emphasises student-centred inquiry and practical engagement (Thomas, 2000). In this respect, the control group's classroom context differed from conventional lecture-based, single-subject teaching models that primarily focus on knowledge transmission. Instead, a degree of learner autonomy and practical application was retained within the instructional design. In practice, teachers in the control group first introduced the necessary subject knowledge and subsequently assigned applied tasks, such as designing and producing a clock dial using software. After acquiring foundational knowledge, students independently developed their designs and tested whether their proposed solutions were feasible for real laser printing. This iterative process of evaluation, modification, and optimisation inherently involves elements of CT, including analysis, judgement, and evidence-based validation. Although such cognitive engagement may not have been systematically scaffolded or explicitly framed as critical reflection, it nevertheless provided students with opportunities to exercise evaluative reasoning.

Consequently, although the control group did not incorporate a structured inquiry framework or explicit knowledge-integration mechanisms comparable to those in the experimental group, the PBL-based approach still created contextual opportunities for the development of CT. In practice-oriented STEM settings, students are required to make decisions, compare alternatives, and assess feasibility when solving authentic problems. These processes, even when not explicitly designed as CT interventions, may contribute to incremental cognitive development. Compared with the experimental group, such opportunities were less structured and less frequent; however, they were not entirely absent. This interpretation may help explain the modest changes observed between the pre-test and post-test results in the control group. Although the magnitude of changes was limited, the inherent autonomy and practical orientation embedded in PBL may have provided a partial foundation for developing. Therefore, the control group outcomes should not be interpreted as entirely ineffective, but rather as reflecting a difference in the degree and structure of cognitive support across instructional approaches.

6. Findings from quantitative data analyses

6.1. Research question 1: changes in CT dispositions

6.1.1. Pre-test for experiment group VS control group

Group Statistics					
	grouping	N	Mean	Std. Deviation	Std. Error Mean
CT disposition	Experimental	90	236.18	17.93	1.89
Pre-test results	Control	88	238.43	20.29	2.16

Table 25: Group statistics for CT dispositions

The pre-test data from the two groups, when approaching large sample sizes ($n > 100$), it shows standard deviation ratios of 7.6% and 8.51% (standard deviation/mean), both less than 10%, indicating minimal fluctuation. Additionally, the SEMs for both groups are less than 5% of their respective means (11.809 & 11.922), reflecting narrow confidence intervals (SEM=1.890 & 2.163). Hence, the pre-test data for the experimental and control groups are relatively concentrated around the mean, displaying high stability and low variability. The low fluctuation (low dispersion) further emphasises that the sample means provide accurate estimates of the population means.

With more minor standard deviation and standard error, the data of both experimental and control groups are more stable. Estimating the mean value is reliable, so the difference between the two groups is more statistically accessible to detect. With less variability within the group, the difference between the groups will be noticeable, which helps to increase the statistical efficiency of the test. It shows a high possibility that the experimental design and data collection process are relatively stable, and the influencing factors are well controlled. Especially in the experimental group, the well-controlled experimental conditions will make the data obtained in this study highly reliable, and the low volatility of the control group makes the pre-test scores of CT dispositions of school S2 and S3 level students nearly identical. Therefore, the data from this pre-test is dependable and effective in controlling the influencing factors and can be used to explain the results of the experiment (the degree of change in students' CT dispositions).

		Levene's Test for Equality of Variances		T-test for Equality of Means					
		F	Sig.	t	df	Significance		Mean Difference	Std. Error Difference
						One-Sided p	Two-Sided p		
Students 'score	Equal variances assumed	.947	.332	-.786	176	.217	.433	-2.25404	2.86843
	Equal variances not assumed			-.785	172.346	.217	.434	-2.25404	2.87243

Table 26: Experimental and control groups pre-test independent samples test

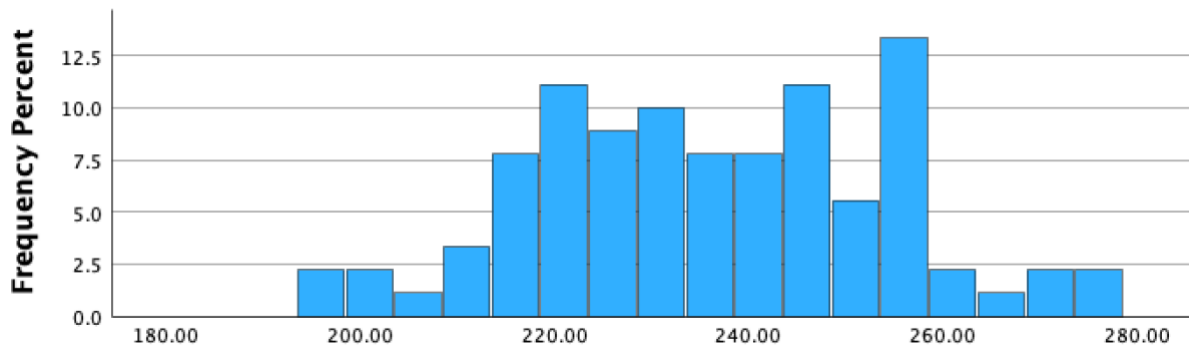


Figure 14: Frequency percent of experimental group in pre-test

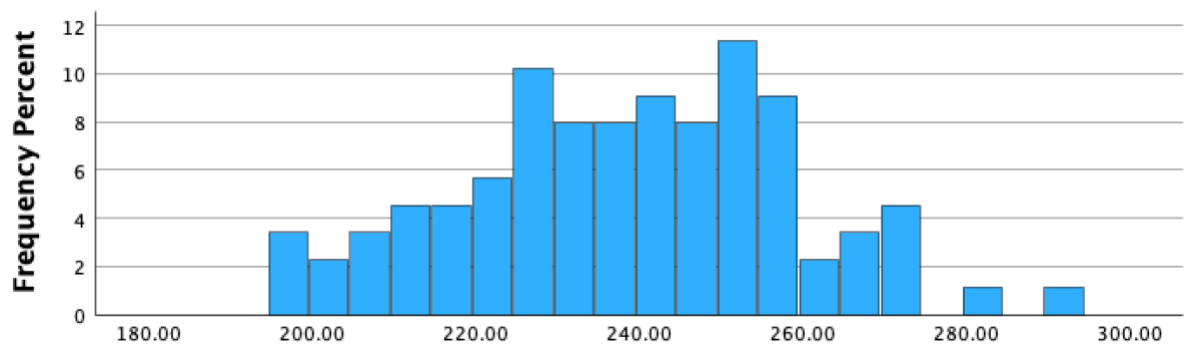


Figure 15: Frequency percent of control group in pre-test

With degrees of freedom (df) of 176 and 172, the sample sizes of both groups are relatively large, which helps improve the statistical test's power. It reflects the relatively small tails of the t-distribution, leading to lower critical values that facilitate the assessment of whether the mean differences are significant. As the degrees of freedom increase, the t-distribution approaches the standard normal distribution. The two histograms above show that the pre-test mean scores

of both the experimental and control groups conform to a normal distribution. In summary, the sample data are substantial ($df = 176$), enhancing the reliability of the tests, and show a normal distribution, which aids in accurately determining the significance of mean differences. Meanwhile, as shown in Table 26, Levene's Test for Equality of Variances, $F=0.947$, the F value is greater than the commonly used significance level of 0.05 ($F>0.05$), which means the two groups have equal variance; no correction is necessary. Two-sided $P = 0.433$ in the independent t -test, $P>0.05$; thus, the statistics are not statistically significant. This demonstrates that the pre-test means scores for CT dispositions between the experimental and the control group are equal, with no significant differences. Therefore, these two data sets can be used as pre-test results to compare with post-test results in the following educational intervention study.

Distribution of the different scoring bands for each group
>350: Strong 280-350: Good 210-280: Not Bad <210: Weak

Figure 16: Distribution of the different scoring bands for CT dispositions.

According to Figure 16, students' pre-test average scores for the two groups range between 210 and 280; the overall CT disposition in participant school S2 and 3 students are 'not bad' according to Peng's standard for the CTDI-CV test. Thus, the overall average scores in the pre-experimental assessment of CT dispositions are moderate and require improvement.

6.1.2. Comparison: CT dispositions pre-and-post test

Variable	Group	N	Mean	Median	Std. Deviation	Range	Minimum	Maximum
Overall	Exp	90	236.18	235.50	17.93	80	196	276
	Con	88	238.43	239.50	20.29	93	197	290
Truth-seeking	Exp	90	31.89	33.00	6.66	33	13	46
	Con	88	32.43	33.00	6.18	30	18	48
Open-mindedness	Exp	90	31.07	32.00	5.21	24	18	42
	Con	88	31.92	32.00	5.55	29	16	45
Analyticity	Exp	90	36.07	36.50	4.02	21	25	46
	Con	88	36.76	37.00	4.49	23	25	48
Systematicity	Exp	90	35.58	36.00	5.13	33	24	57
	Con	88	35.85	35.50	5.05	26	24	50
Confidence in Reasoning	Exp	90	36.18	37.00	7.22	40	14	54
	Con	88	36.81	36.50	6.11	27	24	51
Curiosity	Exp	90	37.23	37.00	6.22	34	21	55
	Con	88	37.18	36.50	4.97	29	24	53
Cognitive Maturity	Exp	90	28.46	28.00	5.72	29	15	44
	Con	88	27.80	28.00	6.56	30	12	42

Table 27: Pre-test CT dispositions scores (include class 3E)

Area/ Metrics	Group	N	Mean	Median	Std. Deviation	Range	Minimum	Maximum
Overall	Exp	63	247.46	247	19.96	115	202	317
	Con	42	237.33	237	22.40	100	176	276
Truth-seeking	Exp	63	33.67	33	6.72	40	20	60
	Con	42	31.62	31.50	5.82	24	20	44
Open-mindedness	Exp	63	33.06	33	4.56	18	24	42
	Con	42	30.93	31	5.57	29	17	46
Analyticity	Exp	63	37.62	37	4.41	25	21	46
	Con	42	36.60	37.50	4.10	20	26	46
Systematicity	Exp	63	37.08	37	4.76	19	28	47
	Con	42	35.95	36	3.58	15	30	45
Confidence in reasoning	Exp	63	38.73	39	6.62	32	23	55
	Con	42	36.67	36	5.30	19	28	47
Curiosity	Exp	63	36.68	36	5.28	26	23	49
	Con	42	36.69	36.50	5.99	33	18	51
Cognitive Maturity	Exp	63	30.49	30	6.71	31	17	48
	Con	42	29.38	30	5.76	25	14	39

Table 28: Post-test CT dispositions scores (include 3E class)

Table 27 and Table 28 display the CT disposition scores for all pre- and post-test students. The number of participants in the control groups for the post-test (n=42) was substantially lower than that of the pre-test (n=88). This reduction is because students from class 3E were unable to complete the post-test for reasons. Consequently, the following content will have two data groups to show the findings: the first one excludes the students' scores from 3E, and the second includes them. The pre-test scores of classes 3E will be excluded from the subsequent primary analyses to ensure the validity and reliability of the data. Nevertheless, researchers may endeavour to present a separate analysis of the original scores of all the students. This approach is contingent upon the specific research question (for example, those analyses that have focused on the post-test only) being addressed and may provide valuable insight into the overall performance of CT disposition dynamics within the cohort.

6.1.2.1. Comparison of students' overall scores between experimental and control groups Overall CT disposition group statistics

Group	Time	N	Mean	Std. Deviation	Std. Error Mean
Experimental	Before	90	236.18	17.929	1.890
	After	63	247.46	19.964	2.515
Control	Before	63	237.41	21.244	2.676
	After	42	237.33	22.402	3.457

Table 29: Group statistics for experimental and control group (exclude 3E class).

After excluding the pre-test scores of the class 3E, the overall data was analysed using SPSS's Independent Samples Test; reasons for choosing this can be found in 4.6.3. Quantitative data analysis plan. Table 29 reveals that the average score of students in the experimental group increased after the intervention project (from 236.18 to 247.46), with a notable improvement of +11.28 points. In contrast, the average score of students in the control group showed almost no change (-0.08). This underlines the efficacy (or similar) of the 7E IBL model as an intervention method, which clearly improved the overall performance in students' CT dispositions. The following section will provide a more in-depth discussion of the significance of the changes based on independent t-test results.

Independent samples test (pre-test & post-test)

		F	Sig.	t	df	Significance		Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
						One-Sided p	Two-Sided p			Lower	Upper
Experimenta	Equal variances assumed	.238	.627	-3.655	151	<.001	<.001	-11.283	3.087	-17.381	-5.184
	Equal variances not assumed			-3.586	124.195	<.001	<.001	-11.283	3.146	-17.509	-5.056

Table 30: Experimental group independent sample test (exclude 3E class)

According to Table 30, includes the Levene's Test for Equality of Variances for the experimental group, $F = 0.238$ and $p = 0.627$. Since $p > 0.05$, it met the assumption of Equal variances, meaning the results are interpreted under the "equal variances assumed" condition. The t-test result at this point, $t = -3.655$, $df = 151$, $p < 0.001$, is statistically significant; it shows a noticeable difference between the pre-and post-test means for the experimental group. The 95% confidence interval for the difference between means is $[-17.381, -5.184]$, so the difference between the pre-and post-test average scores for the experimental group is within this range with 95% confidence. More specifically, there is a 95% confidence that the overall mean scores in the experimental group improved by at least 5.184 points, with the maximum improvement reaching 17.381 points. Thus, it further confirms the effectiveness of the intervention in improving students' overall CT dispositions.

		Levene's Test for Equality of Variances		t-test for Equality of Means						95% Confidence Interval of the Difference	
		F	Sig.	t	df	Significance		Mean Difference	Std. Error Difference		
						One-Sided p	Two-Sided p				
Control Group	Equal variances assumed	.000	.983	.018	103	.493	.985	.07937	4.32519	-8.49863	8.65736
	Equal variances not assumed			.018	84.754	.493	.986	.07937	4.37175	-8.61320	8,77193

Table 31: Control group independent sample test (exclude 3E class)

For the control group, as showed in Table 31, the Levene's Test for Equality of Variances, $F = 0.00$ and $\text{sig.} = 0.983$. $p > 0.05$, so variances are homogeneous, and the results from the "equal variances assumed" can be used. However, the t-test results for the control group indicate $t = 0.018$, $df = 1103$, with a two-tailed p-value of 0.985. The mean difference is 0.07937, demonstrating that the difference between the control group's pre-test and post-test mean scores is minimal (0.07939), almost negligible. This explains that the difference between the pre-test and post-test means in the control group is not statistically significant and can be attributed to random fluctuations rather than any meaningful change over time or the result of any experimental intervention. As the control group was taught using the usual teaching methods (without the intervention), the findings suggest that the CT disposition of students in the control group did not change over a semester's study of STEAM.

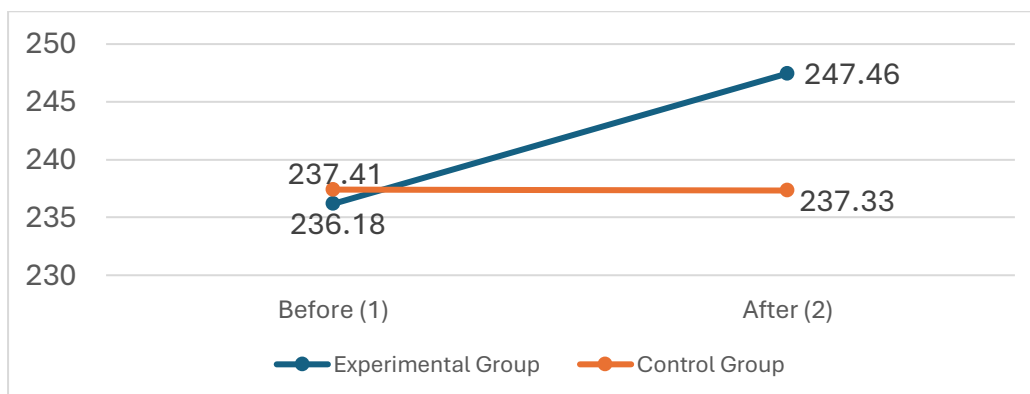


Figure 17: Overall estimated marginal means (exclude 3E class)

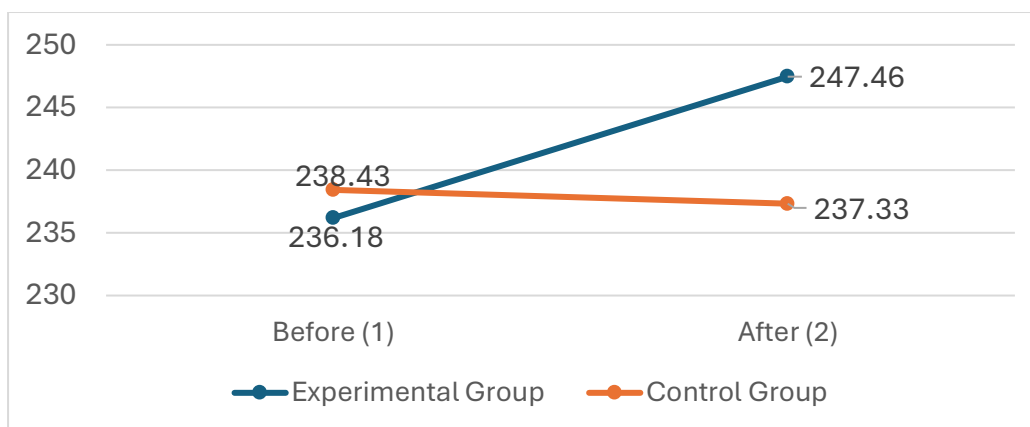


Figure 18: Estimated marginal means (include 3E class)

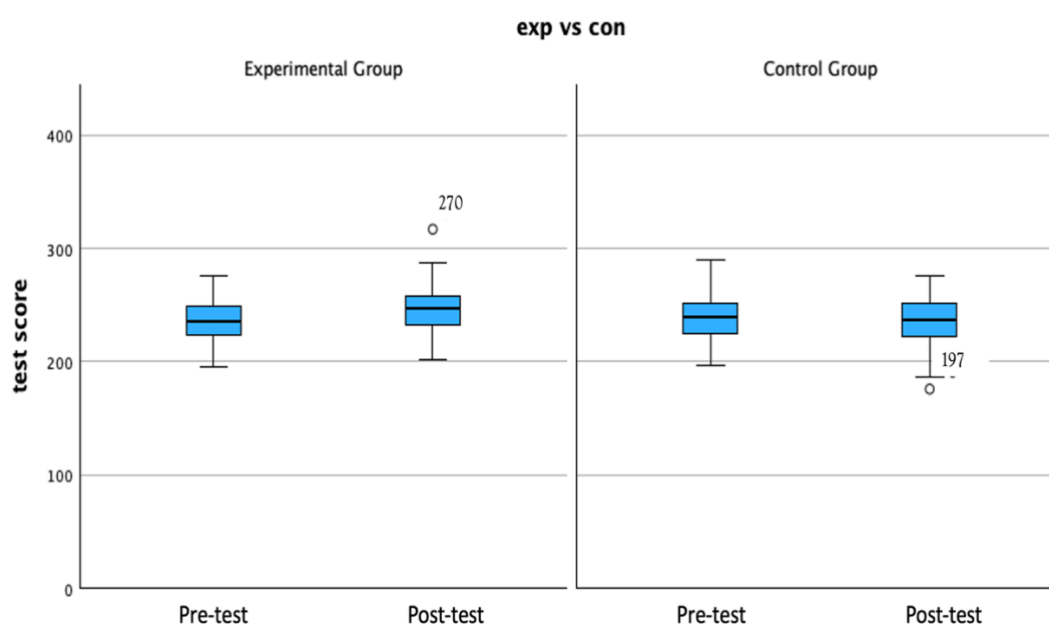


Figure 19: Simple boxplot of CT dispositions Overall score in pre and post-test for experimental and control group.

In summary, after a semester-long intervention project, students in the experimental group had a significant improvement in their overall CT disposition. Figure 17 shows the change clearly: post-test scores tend to be higher than pre-test scores, with the median shifting upward, and more students performed better overall, as there is a broader range. This result was double confirmed by the results of a paired-sample t-test ($n = 63$, $t = -3.655$, $df = 151$, $p < .001$), pointing to a statistically significant change, not something likely to have occurred by chance. On average, students increased their CT disposition's overall score by 11.28 points, which is not just a number which it reflects a real, observable difference in their performance after the

intervention. By contrast, the control group, in Figure 18, did not show a significant shift. Students' pre- and post-test distributions look almost the same in the boxplot in Figure 19. The statistical test supports this as well ($n = 42$, $t = .018$, $df = 103$, $p = .985$), meaning that whatever small change occurred (a decrease of just 0.08 points) was negligible, with no real significance behind it.

Meanwhile both the experimental and the control groups began the study from a comparable level. An independent samples t-test on the pre-test scores in Table 26 shows no significant difference between them (Levene's test: $F = .947$, $p = .332$; $t(176) = -.786$, $p = .433$, two-tailed), suggesting that prior to the intervention, their overall CT disposition was at the same level. Because of this baseline homogeneity, it is more likely that the benefits shown in the experimental group were due to the intervention and not any underlying differences between the groups. As Shadish *et al.* (2002) emphasise, establishing initial equivalence is important in quasi-experimental designs for making valid causal inferences.

		Standardizer ^a	Point Estimate	95% Confidence Interval	
				Lower	Upper
post-test score	Cohen's d	20.968	.483	.086	.878
	Hedges' correction	21.122	.479	.085	.871
	Glass's delta	22.402	.452	.047	.852

Table 32: Independent samples effect sizes comparing post-test CT overall scores between experimental and control groups

Looking further at the post-test comparison between groups, the standardised effect sizes underline the impact of the intervention. Cohen's d in Table 32, was calculated at 0.483 (close to 0.5), with a 95% confidence interval ranging from 0.086 to 0.878, falling within the range generally considered a moderate effect. Hedges' g, which adjusts for small sample bias, produced a very similar value of 0.479, while Glass's delta, which is more conservative by relying on control group variability, yielded 0.452. Although there are some uncertainties, particularly given the lower bound of the confidence intervals, the convergence of these three estimates strengthens the argument that the observed differences are not only statistically significant but also practically meaningful. In other words, the intervention (the 7E IBL model) brought about a modest yet genuine improvement in students' CT dispositions development.

6.1.2.2. Comparison of CT disposition'7 metrics

To examine the differences between the pre- and post-test results of the experimental and control groups, the researcher used ANOVA to analyse each metric in CT dispositions. It further supports the experimental intervention's noteworthy efficacy in raising students' overall CT disposition scores by providing a multifaceted assessment of the effect differences between the two groups. Meanwhile, the ANOVA analysis will look at the between-subject factors (experimental/control group) and within-subject factors (pre-test and post-test). A detailed comparison of post-test scores between the two groups will also be conducted. To confirm the effectiveness of the intervention, the researcher will include all students' data in this analysis, which adds the pre-test scores of students from Class 3E. The main focus will be on between-subjects comparisons, the post-test scores of all students, to provide evidence of the intervention's impact.

Metrics	Group	Time	N	Mean	Std. Deviation	Std. Error Mean
1. Truth- seeking	Experimental (Group 1)	Before	90	31.89	6.659	.702
		After	63	33.67	6.718	.846
	Control Group (Group 2)	Before	88	32.43	6.181	.659
		After	42	31.62	5.818	.898
2. Open Mindedness	Group 1	Before	90	31.07	5.205	.549
		After	63	33.06	4.561	.575
	Group 2	Before	88	31.92	5.555	.592
		After	42	30.93	5.567	.859
3. Analyticity	Group 1	Before	90	36.07	4.019	.424
		After	63	37.62	4.408	.555
	Group 2	Before	88	36.76	4.90	.479
		After	42	36.60	4.097	.632
4. Systematicity	Group 1	Before	90	35.58	5.134	.541
		After	63	37.08	4.756	.599
	Group 2	Before	88	35.85	5.046	.538
		After	42	35.95	3.581	.553
5. Confidence in Reasoning	Group 1	Before	90	36.18	7.221	.761
		After	63	38.73	6.617	.834
	Group 2	Before	88	36.81	6.114	.652
		After	42	36.67	5.299	.818
6. Curiosity	Group 1	Before	90	37.23	6.215	.655
		After	63	36.68	5.282	.665
	Group 2	Before	88	37.18	4.972	.530
		After	42	36.69	5.994	.925
7. Cognitive Maturity	Group 1	Before	90	28.46	5.718	.603
		After	63	30.49	6.710	.845
	Group 2	Before	88	27.80	6.564	.700
		After	42	29.38	5.763	.889

Table 33: CT disposition 7 metrics group statistics (include 3E pre-test)

According to Table 33, from the data analysis, among the seven CT disposition metrics, the post-test average scores of the experimental group improved compared to the pre-test in three metrics, *Truth-seeking*, *Analyticity*, and *Systematicity*. *Open-mindedness*, *Confidence in Reasoning*, and *Cognitive Maturity* metrics were significantly improved, while *Curiosity* slightly declined. In contrast, the control group showed a minor improvement in the *Cognitive Maturity* metric, with little change in *Systematicity* and *Analyticity*, but the remaining five metrics slightly declined. An independent samples t-test will be conducted next, to explore the extent of the changes in these seven metrics between the experimental and control groups and their significance.

Levene's Test
for Equality
of Variances

t-test for Equality of Means

			F	Sig.	t	df	Significance		Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
							One- Sided p	Two-Sided p			Lower	Upper
1. Truth-seeking	Group 1	Equal variances assumed	.265	.608	-1.619	151	.054	.107	-1.778	1.098	-3.947	.391
		Equal variances not assumed			-1.617	132.844	.054	.108	-1.778	1.100	-3.953	.397
	Group 2	Equal variances assumed	.036	.850	.714	128	.238	.476	.813	1.138	-1.439	3.064
		Equal variances not assumed			.730	85.387	.234	.467	.813	1.114	-1.401	3.027
2. Open Mindedness	Group 1	Equal variances assumed	.782	.378	-2.455	151	.008	.015	-1.997	.813	-3.604	-.390
		Equal variances not assumed			-2.513	143.499	.007	.013	-1.997	.795	-3.567	-.426
	Group 2	Equal variances assumed	.011	.917	.951	128	.172	.343	.992	1.043	-1.071	3.055
		Equal variances not assumed			.951	80.638	.172	.345	.992	1.043	-1.084	3.068
3. Analyticity	Group 1	Equal variances assumed	.137	.712	-2.259	151	.013	.025	-1.552	.687	-2.910	-.195
		Equal variances not assumed			-2.222	125.532	.014	.028	-1.552	.699	-2.935	-.170
	Group 2	Equal variances assumed	.024	.878	.203	128	.420	.840	.166	.819	-1.455	1.787
		Equal variances not assumed			.210	87.876	.417	.835	.166	.793	-1.410	1.742
4. Systematicity	Group 1	Equal variances assumed	.025	.875	-1.835	151	.034	.069	-1.502	.818	-3.119	.116
		Equal variances not assumed			-1.860	139.660	.033	.065	-1.502	.807	-3.098	.095
	Group 2	Equal variances assumed	4.846	.030	-.115	128	.454	.908	-.100	.868	-1.817	1.617
		Equal variances not assumed			-.130	109.266	.448	.897	-.100	.771	-1.629	1.428
5. Confid	Group 1	Equal variances assumed	.336	.563	-2.226	151	.014	.027	-2.552	1.146	-4.818	-.287
		Equal variances not assumed			-2.261	140.465	.013	.025	-2.552	1.129	-4.784	-.321

	Group 2	Equal variances assumed	.822	.366	.127	128	.449	.899	.140	1.100	-2.036	2.317
		Equal variances not assumed			.134	92.117	.447	.894	.140	1.046	-1.937	-1.9377
6. Curiosity	Group 1	Equal variances assumed	.797	.373	.573	151	.284	.567	.551	.961	-1.348	2.450
		Equal variances not assumed			.590	145.327	.278	.551	.551	.934	-1.295	2.396
	Group 2	Equal variances assumed	.765	.383	.492	128	.312	.623	.491	.998	-1.483	2.466
		Equal variances not assumed			.461	68.857	.323	.646	.491	1.066	-1.635	2.618
7. Cognitive maturity	Group 1	Equal variances assumed	2.082	.151	-2.017	151	.023	.045	-2.037	1.009	-4.031	-.042
		Equal variances not assumed			-1.961	119.538	.026	.052	-2.037	1.038	-4.092	.019
	Group 2	Equal variances assumed	1.400	.239	-1.338	128	.092	.183	-1.585	1.185	-3.930	.759
		Equal variances not assumed			-1.401	91.033	.082	.165	-1.585	1.132	-3.833	.662

Table 34: Independent samples test for 7 metrics in CT dispositions (include 3E class)

Table 34 shows the independent samples t-test comparing the pre-and post-test mean scores of the experimental and control groups across CT disposition's seven metrics. The results highlighted that the majority of metrics in the experimental group have significant differences, while no significant changes in the control group. According to Levene's test for equality of variances, except for the *Systematicity* metric in the control group, which had unequal variances ($F = 4.846$), equal variances were not assumed for this variable. For all other metrics, equal variances were found, and all data were derived from the output results corresponding to the equal variances. The following section will discuss more details for each metric (include 3E).

Disposition	Overall	1 Truth-seeking	2 Open-mindedness	3 Analyticity	4 Systematicity	5 Confidence In Reasoning	6 Curiosity	7 Cognitive Maturity
Differences 1	11.283	1.778	1.997	1.552	1.502	2.552	-0.551	2.037
Differences 2	-1.099	-0.813	-0.992	-0.166	0.100	-0.140	-0.491	1.585
DID (D1-D2)	12.381	2.591	2.989	1.719	1.401	2.693	-0.059	0.451

Difference 1: Experimental group (Post-test) – (Pre-test). Difference 2: Control group (include 3E class)

Table 35: Difference in differences (DiD) of experimental and control groups

1. Truth-seeking

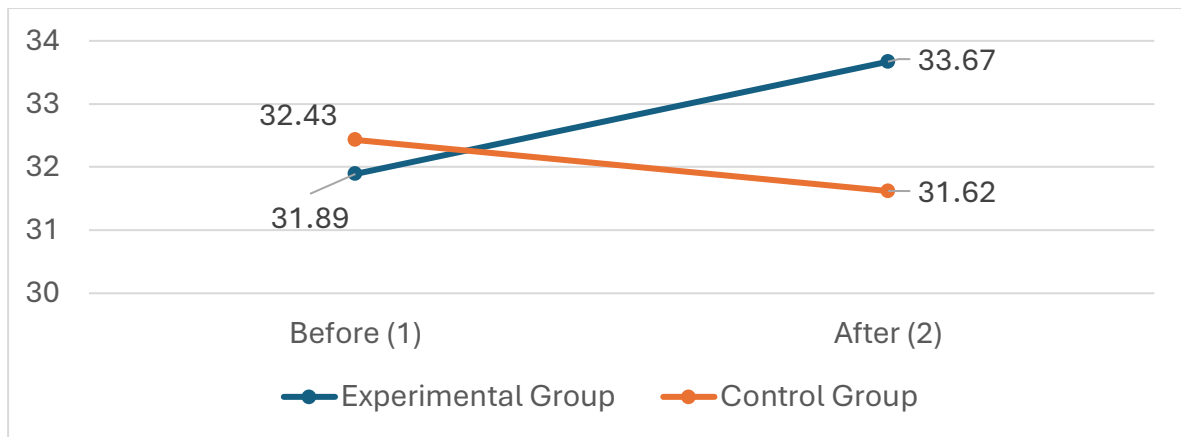


Figure 20: 1. Truth seeking: estimated marginal means

The experimental group's post-test mean score improved by +1.78 compared to the pre-test; however, due to a large standard error ($SE = 1.098$, which is generally considered large when SE exceeds 1), the two-tailed p -value is 0.608 (all subsequent values of p are referred to two-tailed tests and will not be emphasised). As a result, the improvement did not reach a significant level ($p > 0.05$). Meanwhile, the control group decreased 0.81 in post-test, with a p -value of 0.850, did not reach significance ($p < 0.05$). Thus, there were no significant changes in the *Truth-seeking* metric for either group; while the experimental group showed a slight improvement, the control group had a minor decline.

2. Open-mindedness

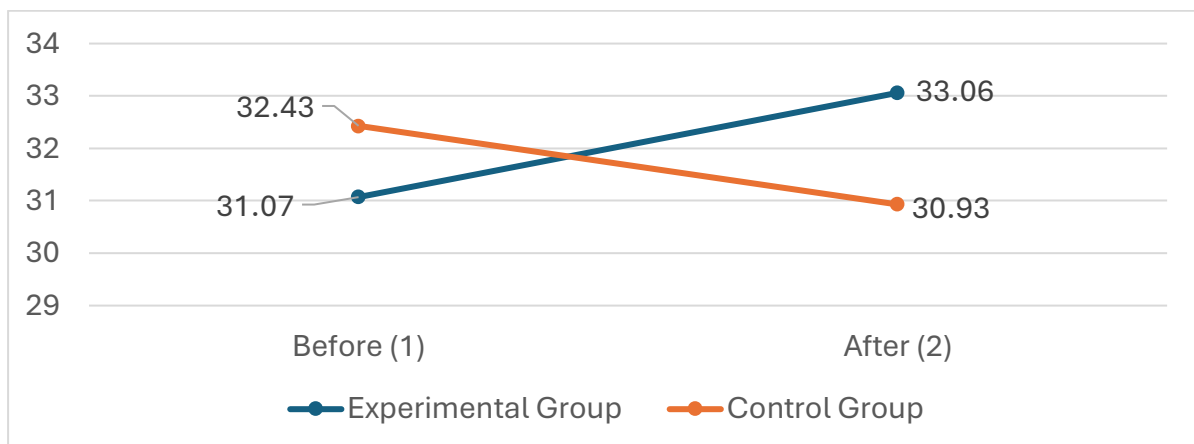


Figure 21: 2. Open- mindedness: estimated marginal means

The experimental group showed a substantial improvement, with a mean difference of +1.997 between the pre- and post-tests ($p = 0.015$; $p < 0.05$). The pre-test minus the post-test scores are represented by the 95% confidence interval, which spans from [-3.604, -0.390]. This means the overall score is expected to improve by 0.390 to 3.604 at a 95% confidence level. On the other hand, the control group did not achieve a significant improvement, $p=0.343$ ($p > 0.05$). These results show a significant overall increase in the experimental group's *Open-mindedness* indicator scores. The control group, on the other hand, displayed a minor decrease of -0.99 but no discernible shift.

3. Analyticity

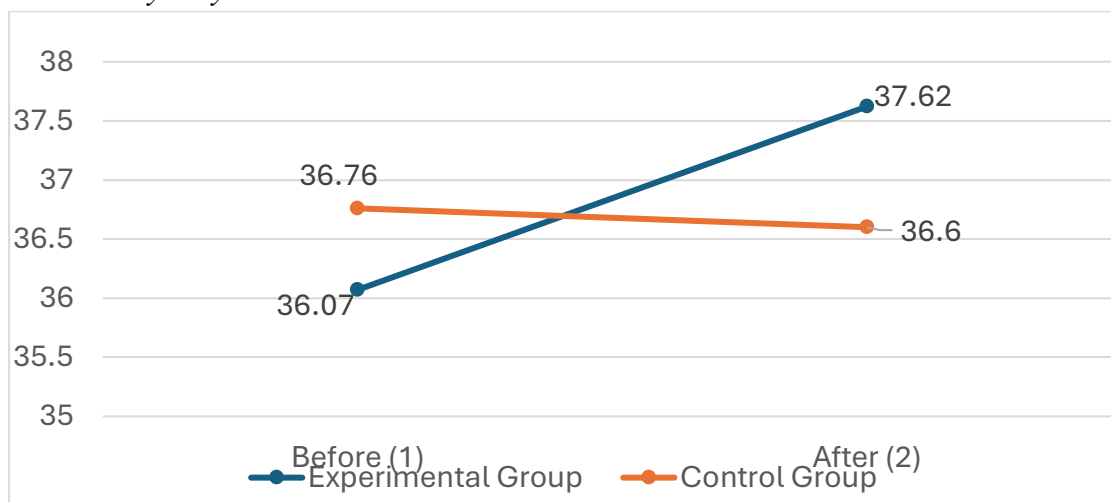


Figure 22: 3. Analyticity: estimated marginal means

The mean scores of the experimental group's post-tests improved by +1.552, with a standard error (SE) of 0.687, considered in a small range (commonly, SE values between 0.1 and 1 are regarded as small). The p -value is 0.025 ($p < 0.05$), indicating a significant level of improvement. At a 95% confidence level, the overall score increased by [0.195 – 2.91] points. As a result, in the control group, $p=0.840$, changed -0.166, there is no significant change. Consciously, the experimental group demonstrated a significant overall improvement in the *Analyticity* indicator, but the control group exhibited little drop.

4. Systematicity

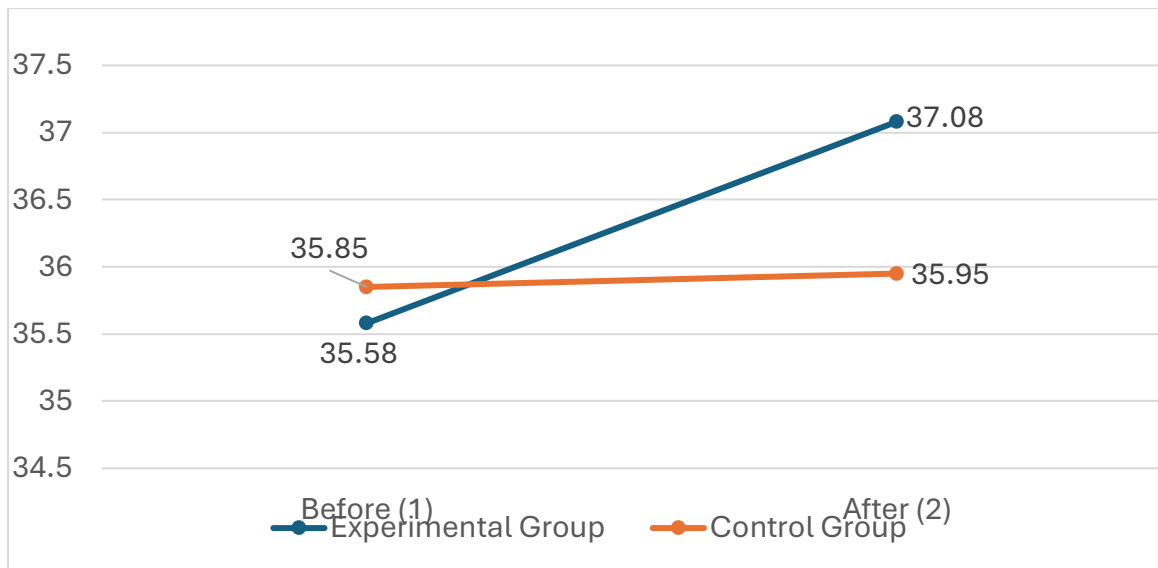


Figure 23: 4. Systematicity: estimated marginal means

In the experimental group, $p = 0.069$, which is not reach but is close to the significance level ($p < 0.05$), and with a mean difference of -1.502 , the confidence interval approaches zero, also because the negative value is substantial ($-3.119 > 0.116$). as a result, it has reached significance; The control group exhibited unequal variances, and $p = 0.908$, which did not indicate significance. Although the experimental group did not meet the statistical significance, it was close to it, with large negative values in the confidence interval and a mean change of $+1.502$, showing an overall improvement in the students' performance. In contrast, the control group showed a mean change of $+0.100$, with minimal score variation and no significant results.

5. Confidence in Reasoning

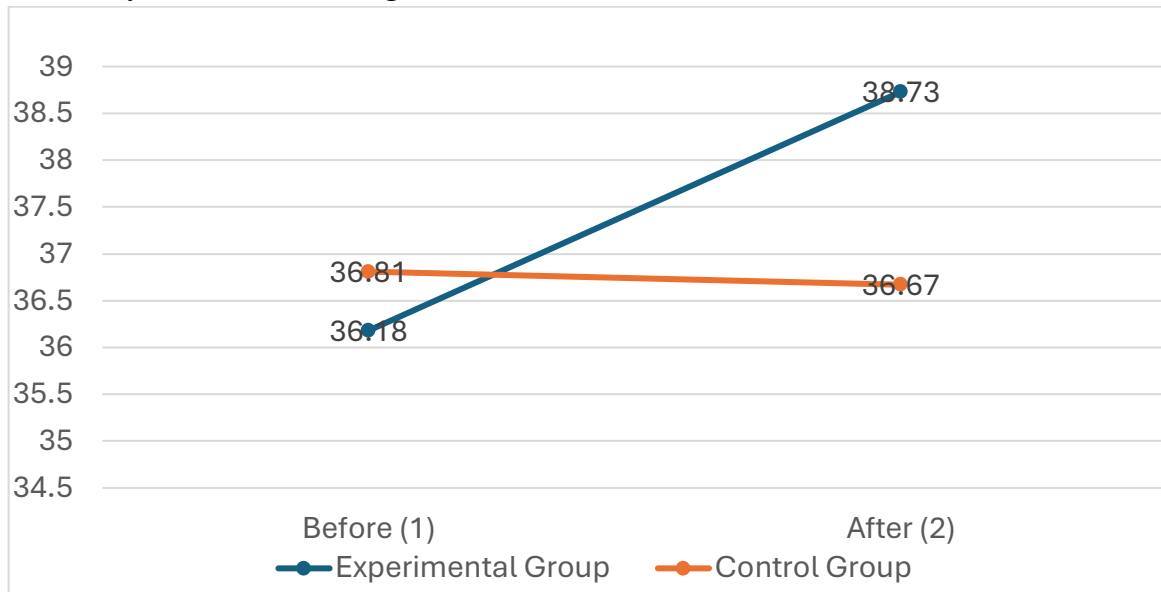


Figure 24: 5. Confidence in Reasoning: estimated marginal means

In the experimental group, $p=0.025$, ($p < 0.05$), the mean difference is $+2.5522$. Thus, in the confidence interval of $[-4.818, -0.287]$, highlighting that there is a significant improvement in *Confidence in Reasoning*. In contrast, the control group shows no significant difference, as $p=0.899$. Therefore, the experimental group's post-test scores for *Confidence in Reasoning* showed a significant overall enhancement. In contrast, the control group's mean change is -0.140 in post-test scores; there is a slight decline, but it did not achieve significance.

6. Curiosity

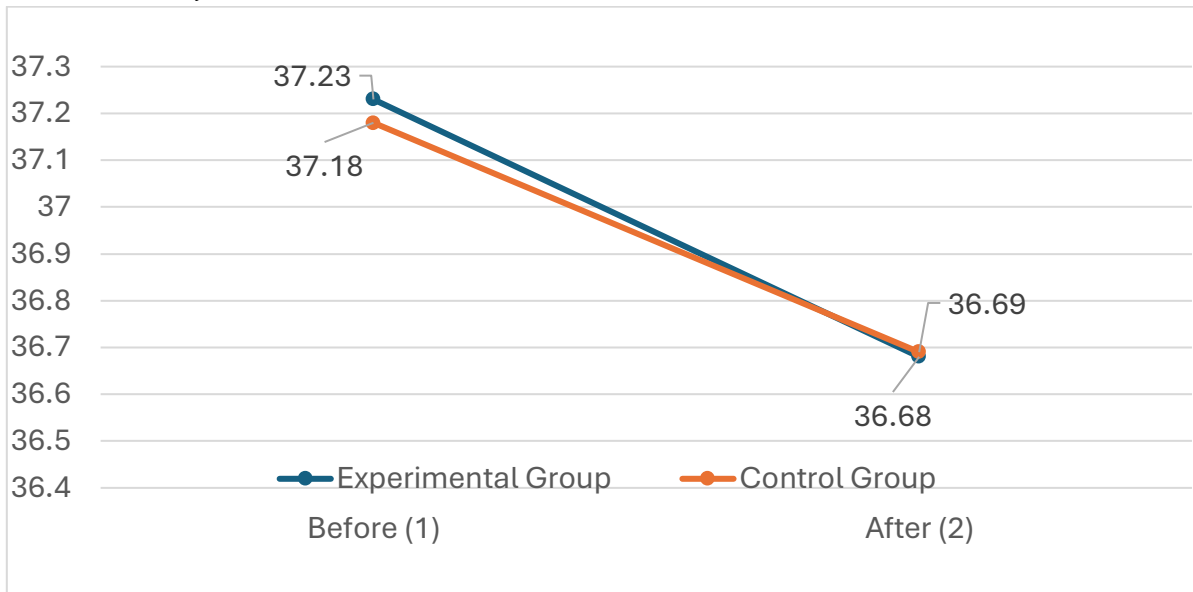


Figure 25: 6. Curiosity: estimated marginal means

In the *Curiosity* indicator, both the experimental group $p = 0.551$ ($p > 0.05$) and the control group $p = 0.623$ ($p > 0.05$), have not reached a significant level. The mean differences for the two groups were -0.551 and -0.491 , respectively, both reflecting slight declines. In short, no matter whether the experimental or the control groups experienced a minor decrease in scores for the curiosity indicator, indicating that the experimental intervention had little impact on this aspect.

7. Cognitive Maturity

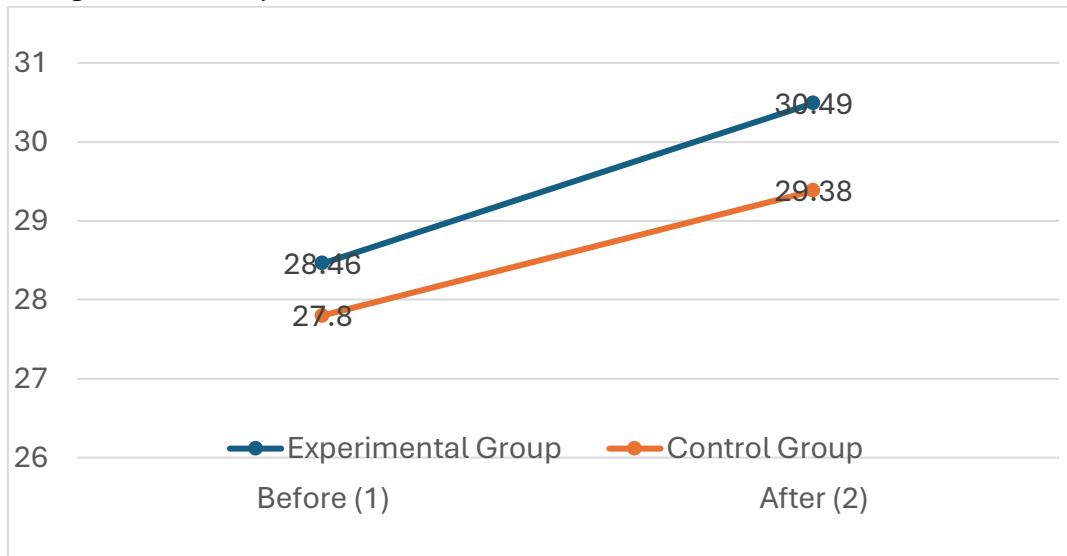


Figure 26: 7. Cognitive Maturity: estimated marginal means

A significant level of improvement could be found in the experimental group, as $p=0.045$ ($p < 0.05$), with a post-test mean score increasing by 2.037 points compared to the pre-test. At a 95% confidence level, the experimental group's mean score significantly improved by between 0.042 and 4.031 points. In contrast, in the control group, $p=0.183$ ($p > 0.05$) did not reach significance, although the post-test mean score showed an increase of +1.585 compared to the pre-test. These results suggest that the experimental group experienced a significant improvement in *Cognitive Maturity*, while the control group, despite not achieving significance, also showed an enhancement in mean scores.

6.1.3. Summary on the changes in students' CT dispositions

Metrics	Changes (Experimental groups)	Changes (control group)
CT Dispositions overall	+++	-
Truth seeking	+	-
Open-mindedness	+++	-
Analyticity	+++	-
Systematicity	+	+
Confidence in Reasoning	+++	-
Curiosity	-	-
Cognitive	+++	+

Significant increase: +++
Increase: +
Decrease: -
Do change: =

Table 36: Summary of changes in students' CT dispositions after intervention

In conclusion, as shown in Table 36, students in the experimental group had significant improvements in four metrics: *Open-mindedness*, *Analyticity*, *Confidence in Reasoning*, and *Cognitive Maturity* metrics, which means the 7E IBL new model has a noticeable positive effect on these aspects. In contrast, the control group had no significant changes in the above metrics (except for a small drop in *Analyticity*). So, the enhancement of students in the experimental group in these four metrics can be attributed to the new teaching model's instructional approach. Although the *Truth-seeking* and *Systematicity* indicators did not reach significance, there were improvements among the experimental group participants at certain levels. Thus, the new teaching model has limited effectiveness on these two metrics. Furthermore, the experimental and control groups experienced slight declines in the *Curiosity* indicator, suggesting that the new teaching model had minimal impact on students' curiosity.

Meanwhile, the *Overall* CT disposition score significantly improved in the experimental group, while the control group remained the same before and after the project (slightly dropped). Its emphasis on applying the 7E IBL model in STEAM education was the primary factor contributing to the improvement of post-test mean scores in the experimental group, rather than natural changes such as the passage of time or other external factors like repeated testing. Thus, the 7E IBL model has significant practical benefits in enhancing secondary school students' CT dispositions within STEAM education. Its effectiveness underscores the value of integrating this model into future teaching practices, making it a valuable pedagogical tool for educators. Moreover, this study lays a solid foundation for further research into instructional strategies within STEAM education, providing a basis for scholars to continue exploring and refining methods for improving student outcomes in this field.

6.2. Research question 2: changes in CT skills

6.2.1. Pre-test for experiment group Vs control group

	grouping	N	Mean	Std. Deviation	Std. Error Mean
CT Skills Pre-test Results	Experimental	53	85.96	4.80	0.66
	Control	66	86.76	4.26	0.52

Table 37: Group statistics for CT skills

		Levene's Test for Equality of Variances		t-test for Equality of Means					
		F	Sig.	t	df	Significance		Mean Difference	Std. Error Difference
						One-Sided p	Two-Sided p		
Students' score	Equal variances assumed	.212	.646	-.956	117	.170	.341	-.795	.83
	Equal variances not assumed			-.944	105.002	.174	.347	-.795	.84

Table 38: Experimental & control groups' pre-test independent samples test for CT skills

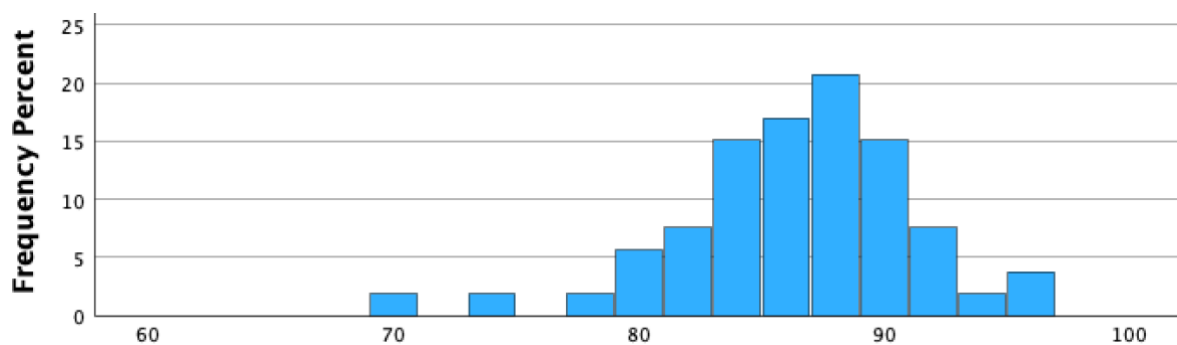


Figure 27: Frequency percent: experimental group pre-test in CT skills

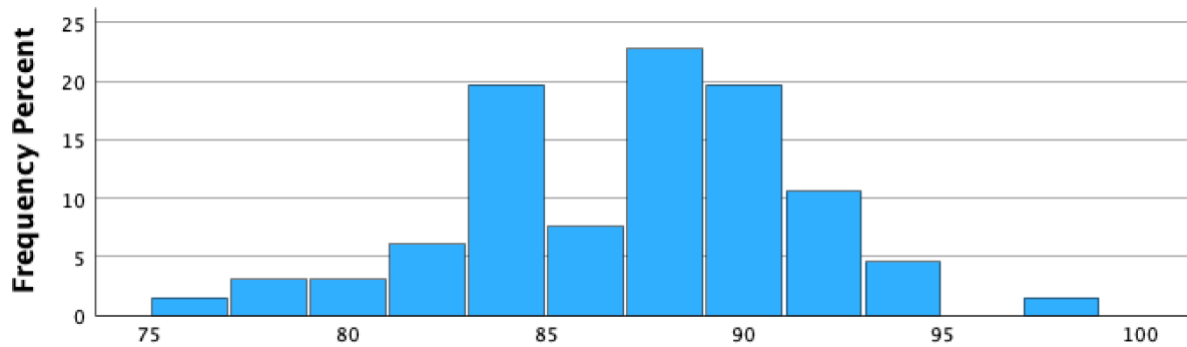


Figure 28: Frequency percent: control group pre-test in CT skills

Following the same analytical approach as with CT disposition, Table 37 and Table 38 show the group statistics and the independent samples test results for the overall CT skills scores of the experimental and control groups. The data indicate that, before the intervention, the mean pre-test CT skills scores of both groups were roughly the same, which can serve as a basis for explaining the effects of the intervention in later comparisons. This is because, firstly, in Levene's test for equality of variances, $F=0.212$, $\text{Sig.}=0.646$ ($p>0.05$), indicating that there was no significant difference in variance between the experimental and control groups. This means the assumption of equal variances is satisfied. Therefore, the results under "Equal variances assumed" were used. Under the assumption of equal variances, the t-test results show $t=-0.956$, $df=117$, and two-sided $p=0.341$, ($p>0.05$), suggesting that the average CT skills scores of the two groups were not significantly different in statistical terms. Secondly, although the experimental group's average score was 0.795 (the mean difference $=-0.795$), lower than the control group before the intervention, the difference was minimal. Finally, the 95% confidence interval $[-2.442, 0.852]$, includes zero, meaning there are increased and decreased in the changes of students' scores, which further confirms that there was no significant difference in the mean pre-test CT skills scores between the two groups. In summary, the two groups' pre-test CT skills scores were similar, with no significant statistical difference, providing a solid foundation for subsequent comparisons of the intervention's effects.

6.2.2. Comparison: CT skills pre-and-post test

6.2.2.1. Comparison of students' overall scores between experimental and control groups

Overall CT skills group statistics

Experimental	Before	53	85.96	4.80	.66
	After	26	87.31	4.04	.79
Control	Before	66	86.76	4.26	.52
	After	27	86.67	5.19	.99

Table 39: Group statistics for experimental and control group in CT skills

The overall data of the experimental group was recalculated and analysed using SPSS's Independent Samples Test, as shown in Table 39 and Table 40. Table 39 reveals that the average score of students' CT skills in the experimental group increased after the intervention project (from 85.96 to 87.31), with a notable improvement of +1.35 points. In contrast, the average score of students' CT skills in the control group showed almost no change (-0.09). This underlines the efficacy (or similar) of the 7E IBL model as an intervention method, which has improved students' overall performance in CT skills. The following section will provide a more in-depth discussion of the significance of the changes based on independent t-test results.

Independent samples test (pre-test & post-test)

		Levene's Test for Equality of Variances		t-test for Equality of Means						95% Confidence Interval of the Difference	
		F	Sig.	t	df	Significance		Mean Difference	Std. Error Difference	Lower	Upper
						One- Sided p	Two- Sided p				
Experimental	Equal variances assumed	.478	.491	-1.231	77	.111	.222	-1.345	1.09	-3.522	.832
	Equal variances not assumed			-1.306	58.225	.098	.197	-1.345	1.03	-3.480	.717

Table 40: Experimental group independent sample test

According to the data in Table 40, $F=0.478$ and $p=0.491$, $p>0.05$, indicating no significant difference in variance between the pre-test and post-test scores of the experimental group. Meanwhile, assuming equal variances and analysing the data under this assumption is reasonable. In this case, the t-test results show $t=-1.231$, $df=77$, one-sided $p=0.111$, and two-

sided $p=0.098$. Since all p -values are bigger than 0.05, this further indicates that the change in the experimental group's CT skills scores between the pre-test and post-test is insignificant, and there is no statistical evidence to support a significant improvement. Thus, although the 7E IBL method has had some effect on improving the students' CT skills, this improvement does not reach statistical significance. However, it is important to note that this does not rule out the possibility of an improvement in the experimental group's scores but instead suggests that the improvement is not statistically significant.

		Levene's Test for Equality of Variances		t-test for Equality of Means							
		F	Sig.	t	df	Significance		Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
						One-Sided p	Two-Sided p			Lower	Upper
Control Group	Equal variances assumed	3.457	.066	.088	91	.465	.930	.091	1.04	-1.972	2.154
	Equal variances not assumed			.081	41.074	.468	.936	.091	1.13	-2.187	2.369

Table 41: Control group independent sample test

In the control group, $F = 3.457$, $p = 0.066$, $p > 0.05$, the assumption of homogeneity of variances is satisfied, and the results from the "equal variances assumed" can be used. However, the t -test results for the control group indicate $t = 0.088$, $df = 91$, with a two-sided $p=0.930$. The mean difference=0.91, meaning that the difference between the control group's pre-and post-test mean scores is minimal (0.91), almost negligible. Meanwhile, the 95% confidence interval is $[-1.972, 2.154]$, and since this includes zero, it further supports the conclusion that there is no significant difference between the two groups. This explains that the difference between the pre-and post-test means in the control group is not statistically significant and can be attributed to random fluctuations rather than any meaningful change over time or the result of any experimental intervention. As the control group was taught using the usual teaching methods (without the intervention), the findings suggest that the CT skills of students in the control group did not change over one semester's study of STEAM education.

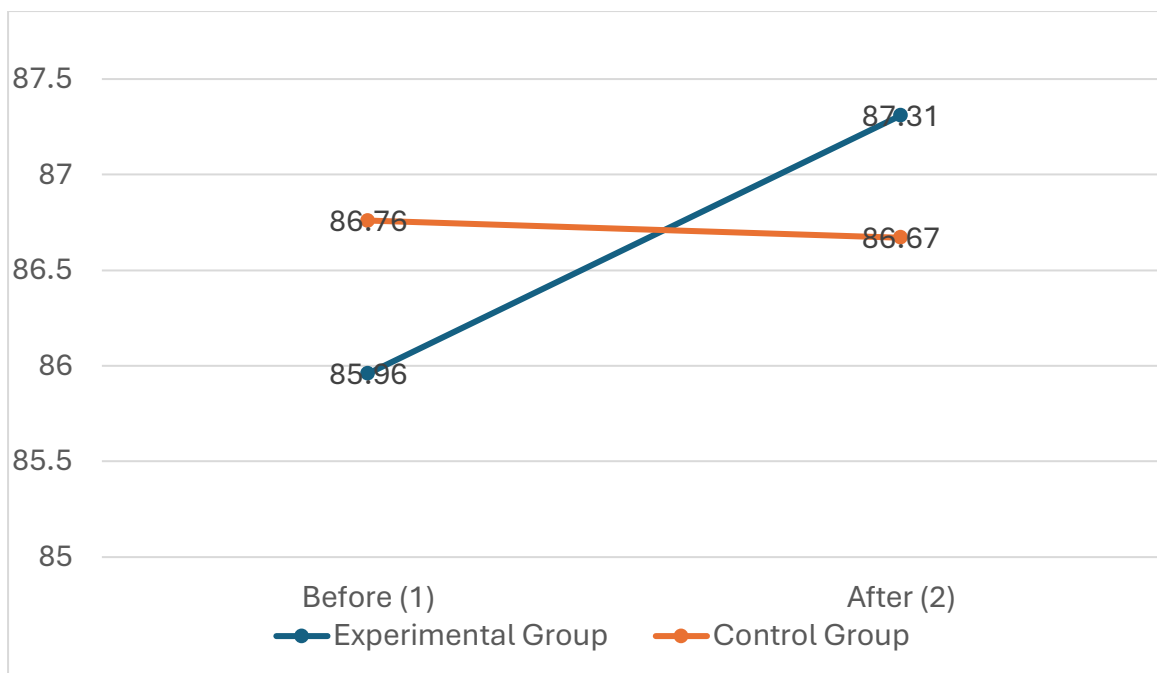


Figure 29: CT skills Overall scores: estimated marginal means

In summary, during the one-semester STEAM education intervention project, students in the experimental group with the 7E IBL model improved their average CT skills overall scores from 85.96 to 87.31, a gain of 1.35 points. However, from a statistical perspective, this improvement did not reach a significant level. Meanwhile, the CT skills scores of students in the control group were slightly decreased from 86.76 to 86.67, with a reduction of 0.09. This change is too small and can be considered negligible. Therefore, although the 7E IBL model has had some effect on improving secondary school students' CT skills in STEAM education, the improvement does not meet the statistical significance.

Comparison the 8 metrics in CT skills

To examine the differences between the pre-and post-test results of the experimental and control groups, the researcher employed ANOVA analysis for each metric in CT dispositions. ANOVA analysis will offer a multifaceted interpretation of the effect differences between the two groups, which will consider between-subject factors (experimental/control group) and within-subject factors (pre-test and post-test), and a detailed comparison of post-test scores between the two groups will also be conducted. This aims to substantiate further the experimental intervention's effectiveness in improving students' overall CT skills scores.

Variable	Group	N	Mean	Std. Deviation	Range	Minimum	Maximum
1. Analysis	Exp	53	87.89	6.62	32	68	100
	Con	66	89.98	5.72	22	78	100
2. Inference	Exp	53	86.64	5.07	25	70	95
	Con	66	88.17	5.40	23	77	100
3. Evaluation	Exp	53	86.83	6.96	27	69	96
	Con	66	86.64	5.82	31	69	100
4. Induction	Exp	53	86.43	4.96	21	74	95
	Con	66	87.08	4.64	21	74	95
5. Deduction	Exp	53	84.83	5.28	25	70	95
	Con	66	86.05	4.87	22	76	98
6. Interpretation	Exp	53	82.91	6.26	26	68	94
	Con	66	83.52	5.29	26	68	94
7. Explanation	Exp	53	83.94	6.50	27	69	96
	Con	66	84.71	6.35	31	69	100
8. Numeracy	Exp	53	84.08	6.11	26	71	97
	Con	66	85.92	6.15	23	71	94

Table 42: ANOVA analysis for pre-test CT skills scores

Area/ Metrics	Group	N	Mean	Std. Deviation	Range	Minimum	Maximum
1. Analysis	Exp	26	90.54	6.14	22	78	100
	Con	27	88.74	7.10	26	71	97
2. Inference	Exp	26	87.54	4.95	21	74	95
	Con	27	87.67	6.60	21	77	98
3. Evaluation	Exp	26	88.31	5.58	19	77	96
	Con	27	86.96	6.39	31	69	100
4. Induction	Exp	26	87.35	3.30	13	80	93
	Con	27	87.85	5.22	19	76	95
5. Deduction	Exp	26	86.77	5.63	22	76	98
	Con	27	85.59	5.75	19	76	95
6. Interpretation	Exp	26	84.50	5.97	26	68	94
	Con	27	85.00	6.75	29	71	100
7. Explanation	Exp	26	85.19	5.43	23	73	96
	Con	27	85.41	6.39	19	77	96
8. Numeracy	Exp	26	87.00	5.07	19	75	94
	Con	27	86.37	6.73	25	75	100

Table 43: ANOVA analysis for post-test CT skills scores

According to the data in Table 42 and Table 43, there is a consistent increasing trend across all metrics of CT skills in the experimental group. Among them, *Analysis* and *Numeracy* had the most substantial increases, with a nearly 3%. In contrast, *inference* and *deduction* showed only minor improvements of less than 1%, while the remaining metrics achieved moderate increases of approximately 2%. However, students in the control group showed instability in their pre-

and post-test scores. Half of the metrics (*Analysis, Inference, Deduction, and Explanation*) declined to varying levels. Minor increases of less than 1% were observed in evaluation, induction, and numeracy, while the interpretation metric showed a more notable improvement of nearly 1.5%. Overall, students in the experimental group had more stable and consistent growth across all metrics of CT skills, reflecting the effectiveness of the intervention method. Conversely, the control group had a fluctuating performance, with a mix of gains and declines, compared to the relatively weaker stability in the students in the control group.

Levene's Test for
Equality of
Variances

t-test for Equality of Means

Group 1:
Experimental Group

Group 2: Control Group

		F	Sig.	t	df	Significance		Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference		
						One-Sided p	Two-Sided p			Lower	Upper	
1. Analysis	Group 1	Equal variances assumed	.129	.720	-1.713	77	.045	.091	-2.652	1.55	-5.734	.430
		Equal variances not assumed			-1.758	53.272	.042	.085	-2.652	1.51	-5.677	.374
	Group 2	Equal variances assumed	3.539	.063	.887	91	.189	.377	1.244	1.40	-1.541	4.029
		Equal variances not assumed			.810	40.425	.211	.423	1.244	1.54	-1.861	4.349
2. Inference	Group 1	Equal variances assumed	.035	.852	-.744	77	.229	.459	-.897	1.21	-3.297	1.503
		Equal variances not assumed			-.751	50.905	.228	.456	-.897	1.20	-3.296	1.502
	Group 2	Equal variances assumed	2.195	.142	.380	91	.353	.705	.500	1.32	-2.116	3.116
		Equal variances not assumed			.349	40.951	.364	.729	.500	1.43	-2.394	3.394
3. Evaluation	Group 1	Equal variances assumed	.499	.482	-.943	77	.174	.349	-1.478	1.57	-4.598	1.643
		Equal variances not assumed			-1.017	60.774	.157	.313	-1.478	1.45	-4.383	1.428
	Group 2	Equal variances assumed	.001	.971	.239	91	.406	.812	-.327	1.37	-3.045	2.392
		Equal variances not assumed			.229	44.577	.410	.820	-.327	1.42	-3.195	2.542
4. Induction	Group 1	Equal variances assumed	3.596	.062	-.849	77	.199	.398	-.912	1.07	-3.051	1.226
		Equal variances not assumed			-.971	69.855	.167	.335	-.912	.94	-2.785	.961
	Group 2	Equal variances assumed	2.075	.153	-.706	91	.241	.482	-.776	1.10	-2.961	1.409
		Equal variances not assumed			-.671	43.690	.253	.506	-.776	1.16	-3.107	1.555

5. Deduction	Group 1	Equal variances assumed	.269	.606	-1.500	77	.069	.138	-1.939	1.29	-4.513	-.635
		Equal variances not assumed			-1.467	47.040	.074	.149	-1.939	1.32	-4.597	-.719
	Group 2	Equal variances assumed	1.930	.168	.386	91	.350	.700	.453	1.17	-1.877	2.783
		Equal variances not assumed			.360	41.063	.360	.721	.453	1.26	-2.085	2.991
6. Interpretation	Group 1	Equal variances assumed	.403	.528	-1.079	77	.142	.284	-1.594	1.48	-4.536	1.347
		Equal variances not assumed			-1.097	52.019	.139	.277	-1.594	1.45	-4.509	1.321
	Group 2	Equal variances assumed	2.996	.087	-1.132	91	.130	.261	-1.485	1.31	-4.091	1.121
		Equal variances not assumed			-1.022	39.693	.156	.313	-1.485	1.45	-4.421	1.452
7. Explanation	Group 1	Equal variances assumed	.970	.328	-.845	77	.200	.401	-1.249	1.48	-4.192	1.695
		Equal variances not assumed			-.898	58.549	.186	.373	-1.249	1.39	-4.031	1.533
	Group 2	Equal variances assumed	.403	.527	-.478	91	.317	.633	-.695	1.45	-3.582	2.191
		Equal variances not assumed			-.477	48.138	.318	.635	-.695	1.46	-3.624	2.233
8. Numeracy	Group 1	Equal variances assumed	.993	.322	-2.108	77	.019	.038	-2.925	1.39	-5.687	-.162
		Equal variances not assumed			-2.248	58.989	.014	.028	-2.925	1.30	-5.528	-.321
	Group 2	Equal variances assumed	.006	.938	-.309	91	.379	.758	-.446	1.44	-3.315	2.423
		Equal variances not assumed			-.297	44.702	.384	.768	-.446	1.50	-3.469	2.577

Table 44: Independent samples test for 8 metrics in CT skills

Disposition	Overall 1	1. Analysis	2. Inference	3. Evaluation	4. Induction	5. Deduction	6. Interpretation	7. Explanation	8. numeracy
Differences 1	1.35	2.65	0.9	1.48	0.92	1.94	1.59	1.25	2.92
Differences 2	-0.09	-1.24	-0.5	0.32	0.77	-0.46	1.48	-0.3	0.45
DID (D1-D2)	1.44	3.89	1.4	1.16	0.15	2.4	0.11	1.55	2.47

Difference 1: Experimental Group (Post-test score) – (Pre-test) Difference 2: Control Group

Table 45: DiD of experimental and control groups

Table 44 presents an independent samples t-test comparing the pre-and post-test mean scores of the experimental and control groups across eight metrics in CT skills. The results indicate that most metrics in both groups had no significant differences. However, significant changes were observed in one metric (*Numeracy*) in the experimental group, and three metrics had almost reached significant differences (*Analysis*, *Deduction*, and *Induction*). Furthermore, the Levene's test $p \geq 0.05$, the null hypothesis cannot be rejected, then the variances across groups are equal, and homogeneity of variances can be assumed. On the contrary, if the p-value < 0.05 , heterogeneity of variances should be assumed. From the table 8 data provided, all p-values (sig.) are bigger than 0.05. Therefore, all indicators assumed equal variances, and all data were derived from the output results corresponding to the equal variances row. The following sections will all follow the above statement.

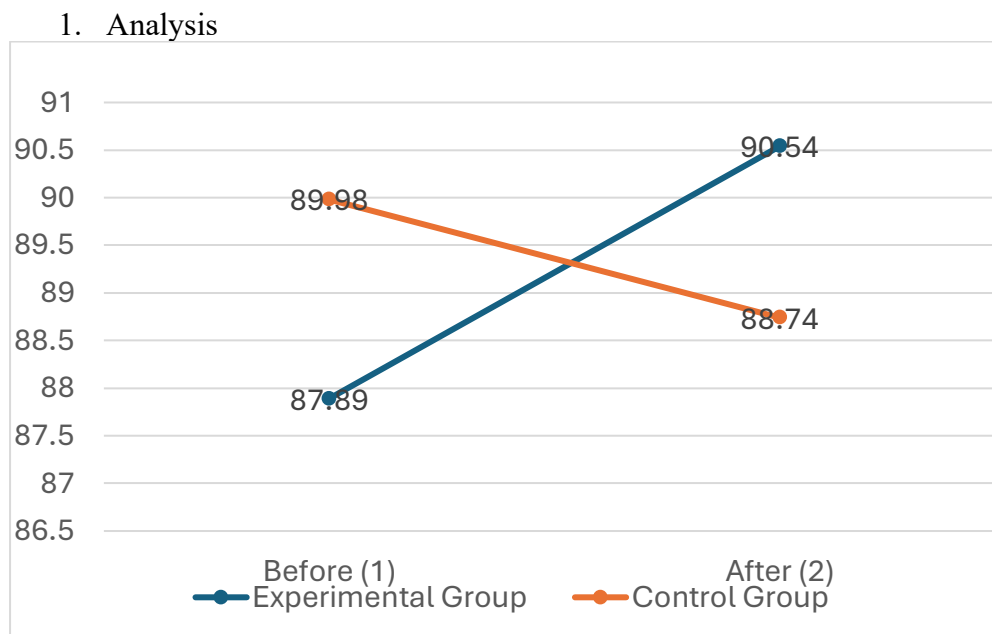


Figure 30: 1. Analysis: estimated marginal means

Based on the data from the experimental group, the students' average post-test CT skills score of the experimental group improved by 2.65 ($D1=2.65$) compared to the pre-test. However, the standard error $SE=1.55$, $SE>1$, showed a considerable variability. Hence, $t=-1.713$, two-sided $p=0.091$ ($p>0.05$), and a confidence interval of $[-5.734, 0.430]$, which includes 0, suggesting no significant improvement in the post-test scores under the two-sided T-test. However, the one-sided $p = 0.045$ ($p<0.05$) indicates a statistically significant difference. On the other hand, the average score of the control group decreased by 1.24 ($D2=-1.24$), with Levene's test

showing a result close to but not reaching significance ($p > 0.05$), $p = 0.036$. Similarly, the two-sided $p = 0.377$ and the one-sided $p = 0.189$, both exceeding 0.05, mean there is no significant difference. In conclusion, for *Analysis* metrics in the experimental group, students' post-test scores did not show a significant change under the two-sided test; there was a significant improvement under the one-sided test. The significant result in the one-tailed test but not in the two-tailed test could be due to the relatively small sample size ($n = 26$ for the post-test, $n < 30$). On the other hand, the control group's score decreased and approached significance but did not reach the threshold for statistical significance.

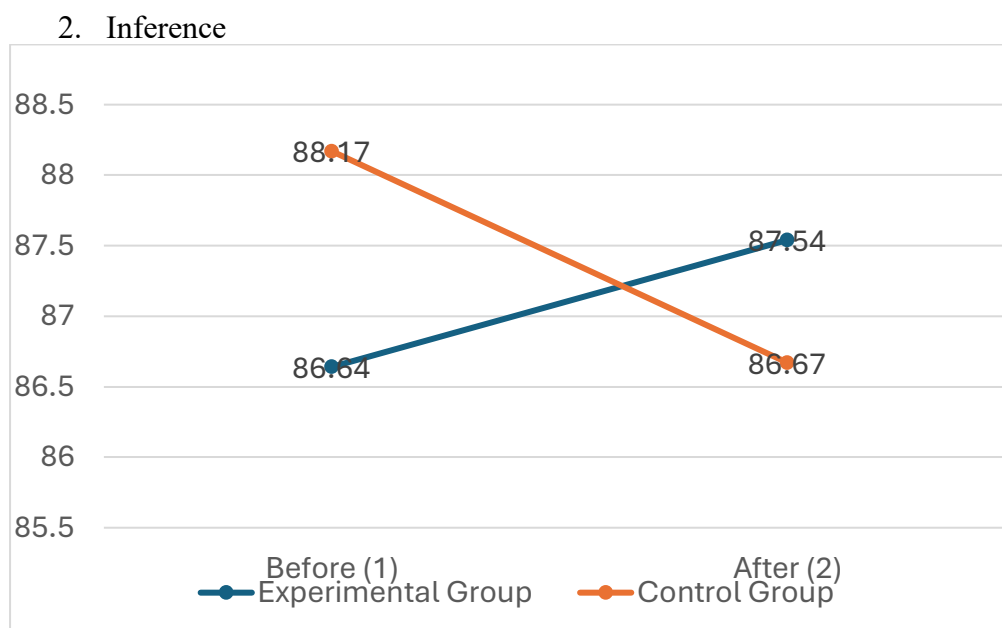


Figure 31: 2. Inference: estimated marginal means

According to the data analysis, the lack of significant changes in the *Inference* metric is emphasised. As shown in Table 45, both the experimental group (mean difference=0.897) and the control group (mean difference=-0.500) showed no statistically significant differences between pre-and post-test scores. In the experimental group, under the assumption of equal variances, $t = -0.744$, with a two-tailed $p = 0.459$, far bigger than 0.05. At the 95% confidence level, the confidence interval was $[-3.297, 1.503]$, including 0. That is the average score of the experimental group students, which could have increased by up to 3.297 points or decreased by 1.503 points, with no significant changes observed before and after the intervention. Similarly, for the control group, the confidence interval was $[-2.116, 3.116]$, also including 0, so some students increased. In contrast, others decreased, as $t = 0.380$ and two-tailed $p = 0.705$,

$p > 0.05$, reflect the non-significant nature of the changes in this group. In summary, in the *Inference* metric assessment, the experimental group's post-test scores showed a slight overall improvement, though not significant, while the control group experienced a slight decline, which was also not significant.

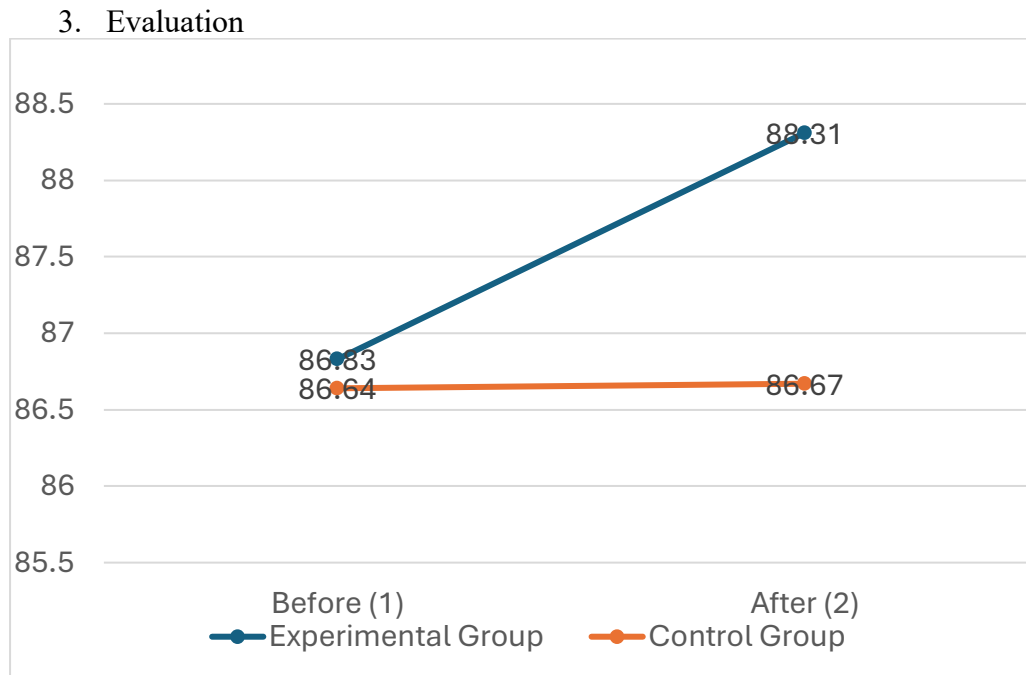


Figure 32: 3. Evaluation: estimated marginal means

In the data analysis for the *Evaluation* metric, the average score of the experimental group students showed a noticeable increase (mean difference=1.478), but it lacked statistical significance. Meanwhile, the control group had almost no change between pre-and post-test scores (mean difference=0.03). The experimental group's $t = -0.943$, with a two-tailed $p = 0.349$ ($p > 0.05$). It is worth noting that although the changes in students' average scores fluctuated without a consistent trend, individual improvements varied significantly, with the highest increase being 4.6 points and the largest decrease being 1.6 points, resulting in an overall slight upward trend. In contrast, the control group showed stable results, with no difference between pre-and post-test scores. Thus, the intervention had a certain positive impact on the *Evaluation* metric and a potential significant change. However, the improvement in the students' average scores did not reach statistical significance.

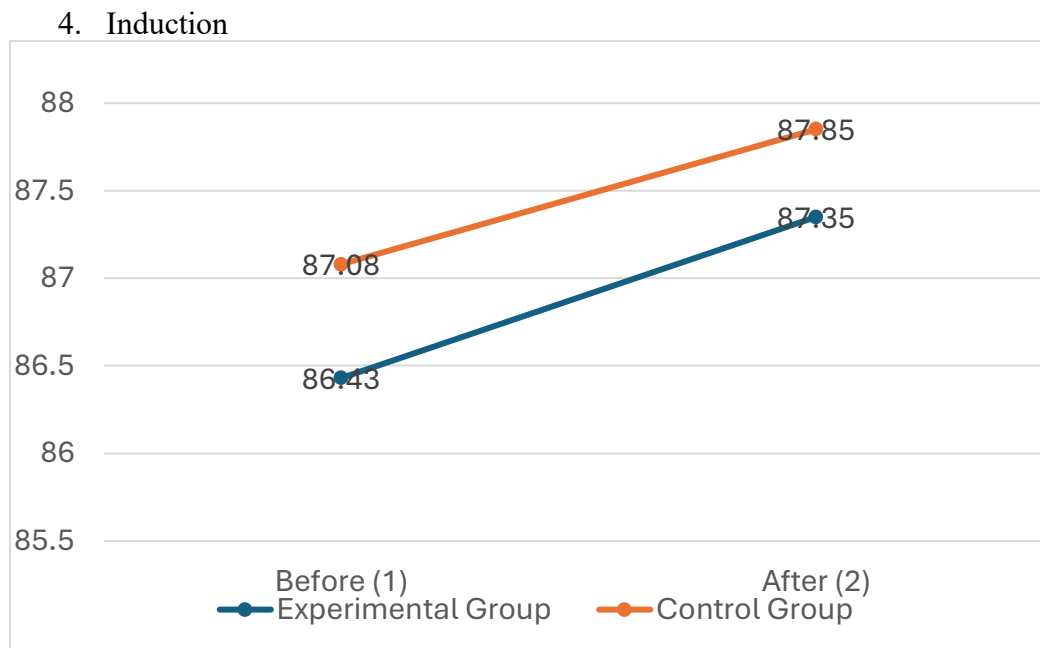


Figure 33: 4. Induction: estimated marginal means

The *Induction* metric data indicate that the experimental group (mean difference=0.912) and the control group (mean difference =0.776) showed a certain degree of overall improvement. However, neither improvement reached statistical significance. In the experimental group, Levene's test revealed $F=3.596$ and $p=0.062$, which was close to the significance threshold ($p<0.1$) but did not meet it. No statistical significance was confirmed in the t-test, where $t=-0.89$, $p=0.398$ ($p>0.05$). In the control group, students' post-test scores also increased slightly. However, $t=-0.706$, $p=0.482$ ($p>0.05$), the observed improvement was not statistically significant.

In summary, both the experimental and control groups experienced improvements in the *Induction* metric. However, the experimental group did not outperform the control group regarding improvement magnitude. Thus, both the new teaching method and the previous method had a positive impact on the induction metric in CT skills. Student performance has improved to a similar extent, even though this improvement is not statistically significant from a scientific perspective.

5. Deduction

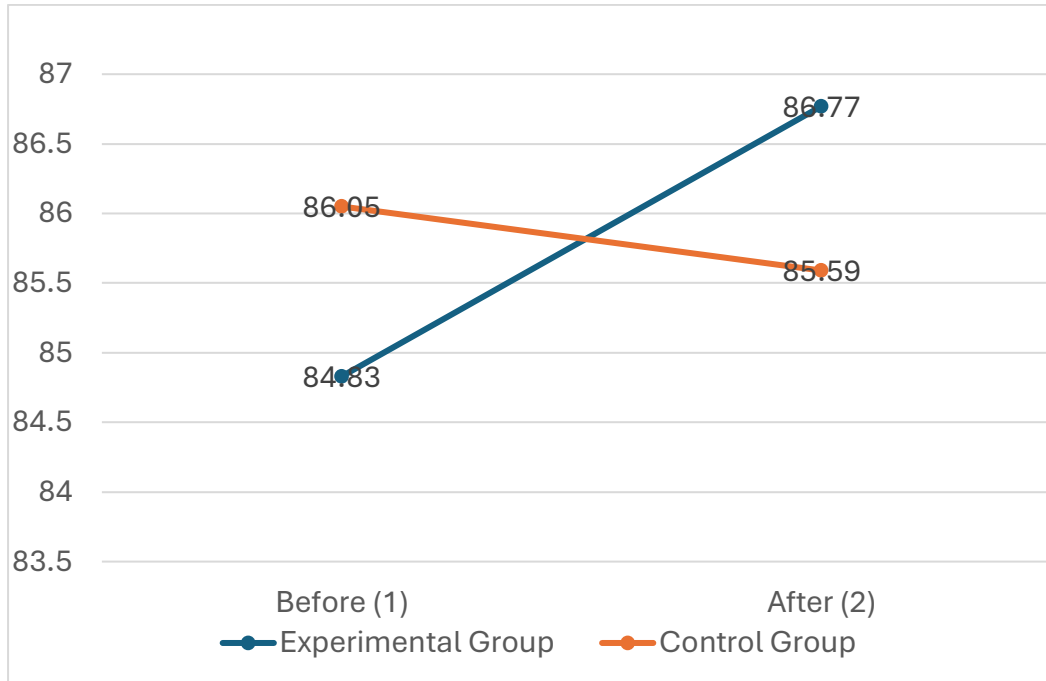


Figure 34: 5. Deduction: estimated marginal means

Regarding the *Deduction* metric, the results reveal an upward trend to some extent, with a mean difference of 1.939 observed in the experimental group. Although this increase did not reach statistical significance ($t=-1.500$, $p=0.149$, $p>0.05$), the confidence interval of $[-4.513, -0.635]$ proved that all students in the experimental group achieved post-test score improvements, with the highest improvement reaching 5.513 points. In contrast, the control group declined by 0.453, but this change was not significant, as $t = 0.386$, $p = 0.7$, $p > 0.05$. Thus, the 7E IBL model improved students' scores in the *Deduction* metric, with potentially significant results.

6. Interpretation

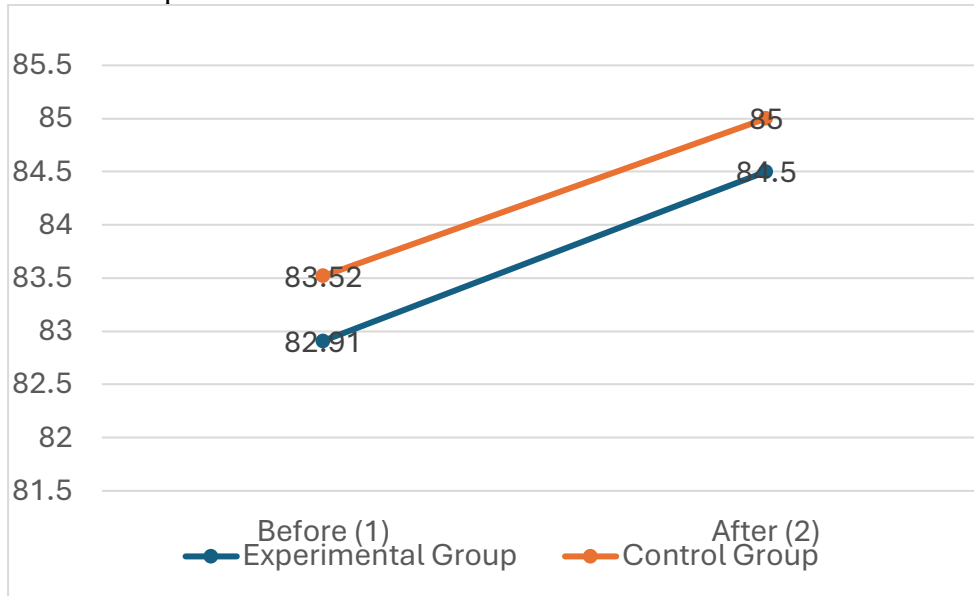


Figure 35: 6. Interpretation: estimated marginal means

The average scores of all students showed a certain degree of improvement in the *Interpretation* metric and had similar levels of improvement, where the experimental group mean difference was 1.594 and the control group mean difference was 1.485. However, Levene's test yielded $p=0.087$ in the experimental group, close to the significance threshold ($p<0.1$). Hence, $t=-1.132$ and $p=0.261$ ($p >0.05$), indicating that a significant improvement in the experimental t-test, $t=-1.132$ and $p=0.261$ ($p >0.05$), indicating that a significant improvement in the experimental group's scores may exist. Although the t-test did not show a clear statistically significant improvement in the experimental group, with $p = 0.261$, the direction of the mean difference was consistent with the expected effect of the intervention. Meanwhile, for the control group, $t=-1.132$, $p=0.261$ ($p>0.05$), so there was no significant improvement in the control group's post-test result.

Thus, similar to the *Induction*, the *Interpretation* metric also had the same conclusion: both the new teaching method and the previous methods used by the teachers have positively impacted the Interpretation. Students' average scores have improved to a similar extent, even though this improvement is not statistically significant from a scientific perspective.

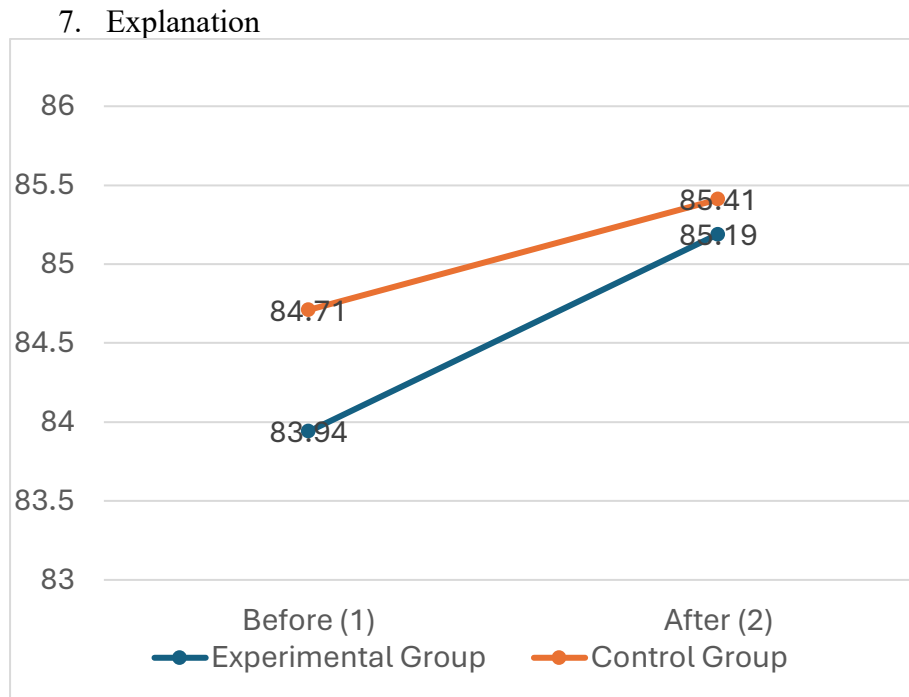


Figure 36: 7. Explanation: estimated marginal means

In the *Explanation* metric, both groups had improvement after intervention, the experimental group's increased by 1.249 and the control groups grew by 0.695. The average score for the experimental group is approximately twice that of the control group. However, despite this difference, neither the experimental group ($t=-0.845$, $p = 0.401$, $p>0.05$) nor the control group ($t=-0.478$, $p=0.633$, $p>0.05$) reached statistical significance in the changes in post-test scores.

Thus, it is indirectly suggested that both teaching methods positively impacted the *Explanation* metric. While the 7E IBL model used in the intervention showed a greater positive effect, the post-test scores for both groups did not significantly improve statistically.

8. Numeracy

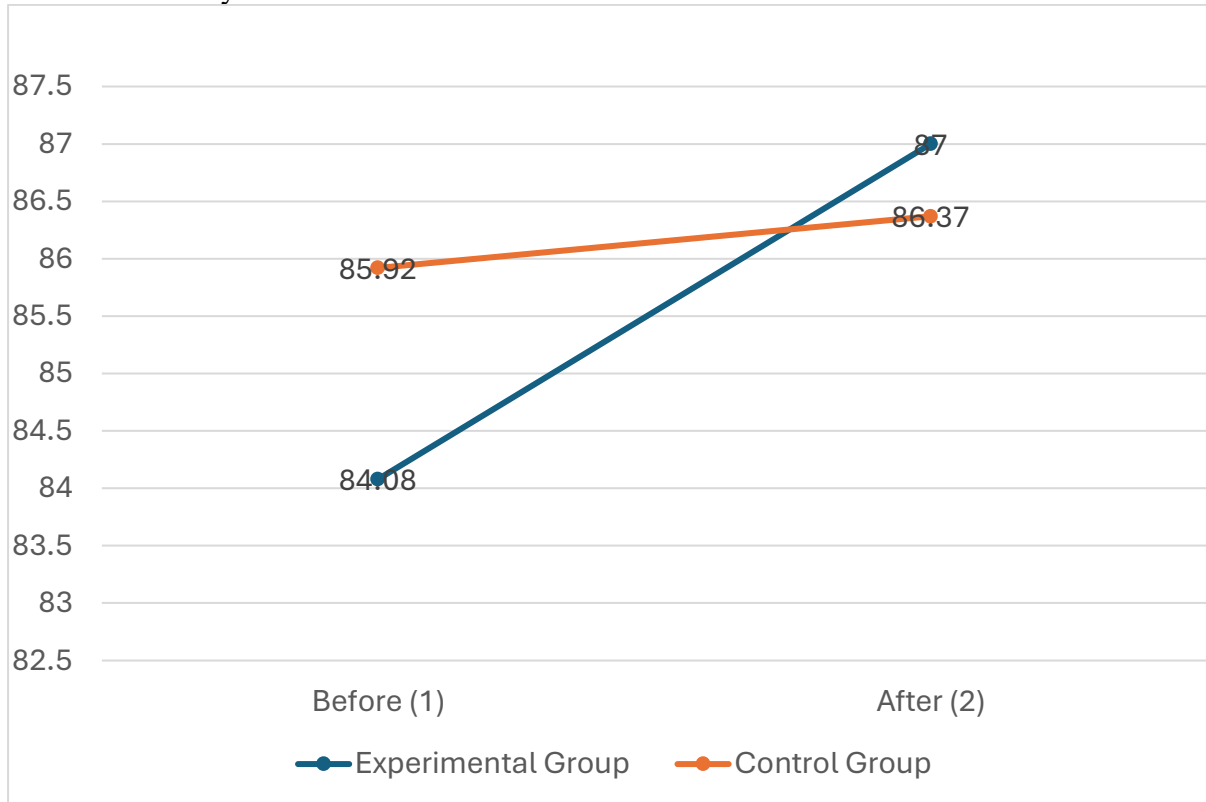


Figure 37: 8. Numeracy: estimated marginal means

The two upward trends in the *Numeracy* metric demonstrate the positive impact of both teaching methods. Notably, *Numeracy* is the only metric within the CT skills where the experimental group showed a statistically significant improvement. The post-test average score increased by 2.925 points, with $t=-2.108$ and a two-sided $p=0.019$ ($p<0.05$). Additionally, the confidence interval $[-5.528, -0.321]$ confirms the significant improvement, with all students' post-test scores increasing and the most significant improvement reaching 5.528 points. In contrast, although the control group also saw an improvement in average scores, the difference ($t=-0.309$, $p=0.758$, $p>0.05$) was not statistically significant. Thus, the results suggest that while both teaching methods improved the *Numeracy* metric, the 7E IBL model used in the intervention had a significantly more pronounced effect.

6.2.3. Summary on the changes in students' CT skills

Metrics	Changes (Experimental groups)	Changes (control group)
CT Skills overall	+	-
1, Analysis	+++	-
2, Inference	+	-
3, Evaluation	++	+
4, Induction	+	+
5, Deduction	++	-
6, Interpretation	++	+
7, Explanation	+	+
8, Numeracy	+++	+

Significant increase: +++

Potential significant increase: ++

Increase: +

Decrease: -

No change: =

Table 46: Summary of changes in students' CT skills after intervention

In conclusion as shown in Table 46, students in the experimental group's post-test results showed different levels of improvement across all eight CT skills metrics, while the control group slightly improved in half of the metrics, with one metric staying stable and three exhibiting a downward trend. With increases of roughly +1.48 and +1.5, respectively, the experimental and control groups' gains in *Evaluation* and *Interpretation* were comparable. However, in terms of *Explanation* and *Numeracy*, the experimental group outperformed the control group. For *Induction*, both the experimental and control group demonstrated a slightly increase. Lastly, for *Analysis*, *Inference*, and *Deduction* the trends in pre-and post-test scores diverged between the two groups, with the experimental group showing an upward trajectory and the control group declining.

As for the level of changes in students' pre-and post-test scores, in the *Analysis*, the experimental group had a significant improvement under one-sided testing, while the control group showed a near-significant decline. Because Levene's test p-values for *Induction* and *Interpretation* were close to the significance threshold ($p < 0.1$), there is the potential for statistical significance. For *Deduction*, the 95% confidence interval [-4.513, -0.632] highlighted that all students in the experimental group improved, and it shows a potentially significant change for this metric. It is worth mentioning that the significant improvements were most evident in the experimental group's *Numeracy* performance.

Overall, the 7E IBL model implemented in the intervention study has increased students' *Overall* CT skills scores and its eight metrics, albeit to varying degrees. While two metrics (*Analysis* and *Numeracy*) showed statistically significant improvement and three (*Evaluation*, *Interpretation*, and *Deduction*) demonstrated potential significance, the intervention's full effects have yet to be realised. The reason for the failure of all metrics to increase significantly might be that the duration of the intervention project was not long enough; the number of participants in the experimental group for the post-test was small, $n < 30$, which resulted in a decrease in statistical effectiveness; or the impact of the model itself was not strong enough. More details for these reasons will be further discussed through subsequent qualitative data analyses in Discussion Chapter.

6.3. Research question 3: The correlation between CT skills and dispositions.

According to the below tables and graphs, the correlation coefficient, $r = -0.130$, falls between no correlation ($r = 0$) and weak correlation ($0.1 < |r| < 0.3$), which means there is almost no linear relationship between CT skills and dispositions but slightly tending towards a negative relation. Because $r = -0.130$ is close to 0, it generally indicates no significant linear relation between skills and dispositions. On one hand, no significant linear relation highlights that students' CT skills and dispositions need to be developed separately, and on the other hand, the development of one should not be substituted for the cultivation of the other. Teachers or school leaders should differentiate between CT skills and dispositions, with a targeted approach to enhance the developmental goal (skills or disposition). However, researchers and scholars believe that CT skills and dispositions are equally valuable because the two are in harmony, and both can strengthen the development of CT. Thus, the researcher suggests schools to develop students' CT skills and the dispositions simultaneously.

Descriptive Statistics			
	Mean	Std. Deviation	N
skills	83.4432	6.50	88
disposition	238.0114	19.90	88

Table 47: Descriptive statistics for CT skills and dispositions: S2+S3

		Correlations	
		skills	disposition
skills	Pearson Correlation	1	-.130
	Sig. (2-tailed)		.229
	Sum of Squares and Cross-products	3675.716	-1458.443
	Covariance	42.250	-16.764
	N	88	88
disposition	Pearson Correlation	-.130	1
	Sig. (2-tailed)	.229	
	Sum of Squares and Cross-products	-1458.443	34460.989
	Covariance	-16.764	396.103
	N	88	88

Table 48: Correlations analysis between CT skills and dispositions

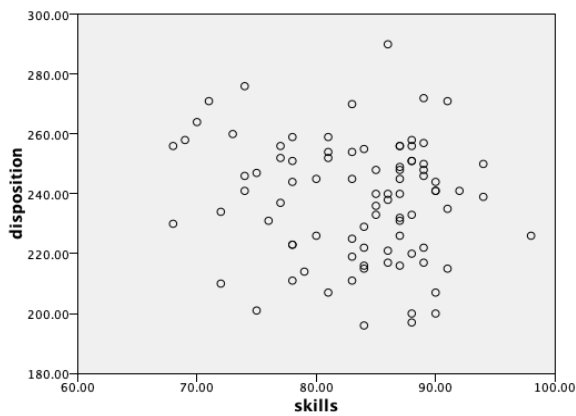


Figure 38: Scatter plot, relationship between CT disposition (x-axis) and skills (y-axis)

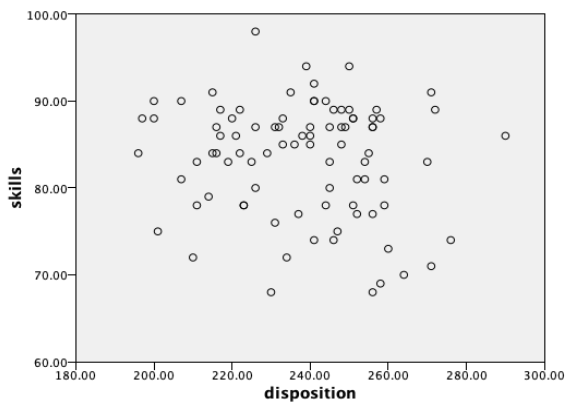


Figure 39: Scatter plot, relationship between CT disposition (y-axis) and skills (x-axis)

It is worth noting that the above finding, indicating an almost negligible correlation between CT skills and dispositions, was based on test data collected from 88 students within the context of secondary school education in Hong Kong. Therefore, it remains possible that these two constructs may be related under different educational levels or student backgrounds, as reported in previous studies. For example, Profetto-McGrath's (2003) research on undergraduate nursing students has found a positive correlation between CT skills and dispositions. Although further research is needed, the present findings in this project suggest that the relationship between these two constructs may vary across different educational contexts, thereby providing alternative empirical evidence and informing future research directions.

7. Findings from qualitative data analyses: examining changes in students' CT in different dimensions

During the qualitative data collection and analysis of the study, interview transcripts were analysed thematically to identify recurring patterns and categories relevant to the research questions. As the researcher was solely responsible for conducting and coding the interview data, inter-rater reliability was not applicable. Instead, the trustworthiness of the qualitative findings was supported through member checking (by one participating teacher and the researcher's supervisors) and maintaining a transparent audit trail of the coding process, which are useful strategies for enhancing credibility in qualitative research (Birt et al., 2016). According to the qualitative data, the interviews with STEAM education teachers, the following analysis will focus on students' performance across various dimensions, including classroom questioning, overall classroom performance, mastery of subject knowledge, and the completion of classroom coursework. Through these aspects, the study will explore changes in students' CT skills and dispositions following the intervention experiment.

7.1. Students' questions during lessons

Student questioning can provide important information into their learning and cognitive processes, particularly in the context of scientific inquiry-based learning environments (Chin & Osborne, 2008). Regarding questions themselves, they reflect students' cognitive activities, demanding the application of various higher order thinking skills, including CT (Hu et al., 2019). Furthermore, Hu et al. (2019) proposed an effective questioning strategy and demonstrated its efficacy in promoting students' CT abilities. Numerous studies have shown that, in inquiry-based classrooms, analysing the questions posed by students can reveal, to some extent, the depth of their understanding of the content and the manifestation of related skills, such as CT (Hu et al., 2019). Therefore, in analysing teacher interview transcripts, the researcher will examine the quantity and content of student questions and, through relevant examples explore the differences in CT skills between the experimental and control groups during classes.

7.1.1. The numbers of questions

Three of the four teachers (Teacher A, B, and C) observed that students in the experimental group were generally more inclined to ask questions than those in the control group. At the

beginning of the intervention, many of these students were still unfamiliar with how to formulate meaningful questions; however, with consistent guidance and encouragement from their teachers, they gradually developed confidence and competence in questioning over time. However, teacher D believes students in the experimental group asked less questions than the control group. The reason will be further explained in the section on "Content of Questions."

During group discussions, students in the class taught with the new teaching approach tended to raise more questions than those in the traditional class. (Teacher C)

In the experimental group, at the beginning, students struggled to ask deep questions. But with our guidance and encouragement, the more time they have, they gradually learned how to ask more questions and became quite confident by the end. (Teacher A)

I think the students in the class using the new method seemed to ask slightly fewer questions, as they tended to take the initiative to solve problems by themselves. (Teacher D)

Teachers highlighted that the increase in the number of questions posed by students was closely linked to the opportunities and time provided for reflection and collaboration. According to one teacher, "Without a deliberate push from teachers, the number of questions tended to decline not only during the inquiry activities but also at other stages of the lesson" (Teacher A). In sum, the increase in questioning was particularly increased when teachers created opportunities for student interaction, such as during discussions in inquiry activities and Q&A sessions during project presentations. In contrast, significantly fewer questions were observed in the control group's classroom.

When we gave them more time to think and discuss, the number of questions increased. But when class time was limited, we asked them to think on their own and come to us with their questions after class. (Teacher A)

During the first one or two lessons using the new teaching model, we had to give the students in the experimental group more guidance so that they would understand what kinds of questions to ask. However, after two or three sessions, they began to ask questions more spontaneously and interactively with one another. They also started to raise questions not only during the designated inquiry periods but throughout other parts of the lesson as well. (Teacher B)

If we deliberately cultivate their CT in class and encourage them to communicate with their peers during inquiry, they will be better able to ask meaningful questions, not just superficial ones. (Teacher B)

Overall, from the perspective of the average number of questions asked per lesson, there were substantial differences between students in the experimental and the control group. Specifically, "students in the experimental group asked substantially more questions per lesson (eight to ten) than those in the control group (three to four)" (Teachers A and B). The questions raised by the experimental group often explored or extended new knowledge, while those from the control group mainly related to prior knowledge. It indicates that the 7E IBL model created a supportive environment for students to shift from passive recipients of knowledge to active inquirers. At a deeper level, students' behavioural change reflects an emerging capacity for CT and independent thinking fostered by the new model.

7.1.2. The content of the questions

- In control group

Teacher D who believed that students in the control group asked more questions was due to a different focus on question types compared to the other teachers. Students' questions are broadly categorised by researcher into two types: 'ordinary' questions related to prior learning or technical questions concerning software operation, and 'advanced' questions involving the extension of knowledge (the advanced questions are further divided into 4 types in next paragraph). Teacher D tended to focus more on technical questions, which are the ordinary questions that were raised more for students in the control group. In contrast, the other three teachers referred to advanced questions related to knowledge extension or those arising from students' CT; they believed students in the experimental group ask more advanced question. As an example, in actual classroom teaching, "ordinary questions" often manifest when students work on 3D projects and need clarification on software operations covered in previous or earlier lessons. In the control group's classroom, teacher D observed that such "ordinary questions" appeared frequently during the inquiry phase, particularly when students began independently creating their projects. In the experimental group's classroom, the occurrence of these ordinary questions was noticeably lower. And this is the main reason why the teacher D

believed students in the control groups asked more questions than those in the experimental group.

For instance, students in control group may have already been taught how to draw a straight line using the software. However, due to insufficient mastery of this skill, they repeatedly ask the teacher how to execute this function during practical application. (Teacher D)

- In experimental group

According to the teacher interviews, the researcher categorised students' questions posed in lessons into five main types. 1) questions that remained unresolved despite independent thinking; 2) questions related to knowledge extension and expansion; 3) questions that demonstrated a higher level of difficulty and deeper CT; 4) questions related to problem-solving; and 5) the ordinary questions. The majority of questions raised by students in the experimental group were low in "ordinary questions". The following section will illustrate specific cases from actual teaching practice.

- 1) Firstly, questions that remain unresolved after independent thinking typically arise during group discussions.*

These types of questions arise from students' difficulties in providing a reasonable explanation for a particular theory or phenomenon in new knowledge, even after engaging in self-directed exploration. Formulating and answering such questions contribute to the development of students' CT, particularly their ability to interpret, (seeking and linking meanings and context-specific relevance), and their ability to explain, which involves providing well-reasoned and evidence-based justifications for conclusions. It demonstrates the extent to which students are engaged with the material and motivates them to deepen their comprehension and build a solid knowledge base through group discussions. In such situations, students could turn to their teachers for guidance or participate in group discussions in an effort to enhance their understanding. From one perspective, this process depends on independent inquiry and deep thinking while embodying a key characteristic of CT in education: thinking about thinking.

Students in the experimental group tended to discuss and solve problems within their small groups by sharing ideas. The questions they asked were usually more specific and

challenging; only when they really couldn't solve an issue would they come to the teacher. In contrast, students in the control class tended to ask about everything before they even started working, showing less confidence in solving problems independently. (Teacher D)

Thus, students in the experimental group began to demonstrate CT, deepening their cognitive engagement through reflection and collaboration. These findings indicate that the 7E IBL model effectively fostered peer interaction and greater independence in problem-solving. Compared with the control group, students in the experimental group exhibited stronger self-regulation and a more critical, analytical approach to learning, whereas those in the control group continued to rely heavily on teacher guidance.

2) *The second category of questions highlighted the exploration and extension of knowledge.*

They were building upon the first category and emerging progressively in the later stages of the lesson, which is after the inquiry section. In the 7E IBL model, teachers summarise key subject knowledge in the final extension phase and encourage students to extend their learning autonomously by generating new questions based on the concepts covered in the lesson. Consequently, this stage often sees a surge in extension-related questions linked to the lesson content. Such enquiries cover a wider range of divergent thinking and go beyond product design. For example, "in a session on laser cutting, students investigated if the technology might be used to produce various kinds of goods, how mass manufacturing could be accomplished, or even how the products could be released onto the market" (Teacher C). Another example is that "when we used drones in class, some students started wondering whether cars could also be designed to become driverless" (Teacher C). Such extension of thinking is in line with the 7E IBL models' intended learning goals, which encourage students to apply newly learnt material, extend classroom instruction outside of the classroom, and integrate it with real-world contexts to enhance their comprehension. This pedagogical approach is also consistent with the core objectives of STEAM education, which aim to foster inquiry-based learning in authentic contexts. More importantly, in the experimental group, students had begun to ask these types of questions spontaneously. They no longer relied heavily on teachers' prompts; instead, the positive classroom atmosphere encouraged them to take the

initiative to raise questions on their own. Although the proportion of students exhibiting a proactive approach to exploration has increased, this is still rather small, and students in the control group have hardly ever asked questions of this nature. It shows that professors are still very important in helping pupils do their own research. Thus, a key issue warranting further discussion is how to stimulate students' ability to extend their learning independently more effectively.

Students in the class using your teaching method asked more extension type questions because they had more time for discussion, and the classroom atmosphere was more active. They were enthusiastic and didn't need much pushing from us. Some even started wondering whether they could use the skills they had learned to start their own businesses. Although there were only a few cases like this, perhaps two or three students in a class, it did happen. None of the students in the control group raised such questions. (Teacher C)

- 3) *The third kind of inquiry mostly used CT and usually required deeper levels of thought and greater cognitive effort.*

Although the structure of these questions may be similar to that of the first category, their fundamental differences are substantial. The core feature of these questions is that they not only focus on understanding and applying foundational knowledge but also emphasise optimising and improving the performance of existing products from a critical perspective, thereby increasing the complexity of the problem. These questions often span a broader range of knowledge areas, extending beyond the essential content taught in the classroom, and can be regarded as far-transfer problems, which require leveraging existing knowledge while introducing more challenging advanced knowledge. For example, teacher B explained:

A student posed the following question: *When designing a clock surface by laser cutting, how could the clock automatically run through the integration of other technologies, thereby reducing reliance on the current battery-powered design?* (Teacher B)

The formulation and resolution of such questions reflect students' application of CT skills in refining and optimising existing designs, including the analysis of complex problems, inference, and the practice of innovation. Among these, analysis and inference are core competencies

emphasised within CT skills. Furthermore, the ability to make well-considered judgements in complex situations aligns with the induction skill in CT. Similarly, such questions were only seen in the experimental group (although the number was low), not the control group. This emphasises even more how a proper teacher and knowledge expansion may effectively stimulate students' CT and encourage them to use deeper levels of thinking in a teaching environment that follows the new paradigm.

4) Problem-solving questions are the fourth type of questions raised by students from experimental groups.

These questions involve CT, and, more importantly, their essence lies in the students' active exploration of potential solutions as they pose the question. This implies that students actively use their prior knowledge to reason or hypothesise solutions after identifying a problem, creating initial responses in the process. They then hone their concepts through instructor consultations or group discussions in an effort to find more effective tactics. When such questions start to appear, it usually means that students are trying to apply what they have learnt in real-world situations and are moving from passively absorbing information to actively creating it. Students' questions, for instance,

If a wider variety of materials might be used with laser cutting (they have been instructed to use wood boards as of right now). Based on their existing technical knowledge, they may then propose adjustments such as altering laser power or optimising cutting paths to use stainless steel boards and seek feedback from group members and teachers. (Teacher D)

When using a 3D printer, we asked students to give presentations introducing their own products, and then other students were asked to provide feedback. In the class using the new method, the comments and questions students offered were not merely critical; they also included constructive suggestions and possible solutions. The control group (has one presentation at the end of the semester) did not have any questions, or the suggestions they gave might just be based on daily life, and they might not necessarily provide a solution for the students. This was the biggest difference between the two groups. (Teacher B)

These questions' serve to deepen disciplinary knowledge and foster CT skills, team collaboration, and innovative thinking. Within an IBL model, the appearance of problem-solving questions often indicates that students are able to transfer classroom knowledge flexibly to new problem scenarios. This process is consistent with the theory of transfer of learning, which emphasises the application of prior knowledge to novel contexts (Perkins & Salomon, 1992). Their solutions become increasingly innovative and workable through constant integration and improvement. Problem solving questions require more of students' general competencies, such as problem identification, logical reasoning, experimental design, and teamwork, than the other three categories. Therefore, in teaching settings, providing the necessary resources and guidance is essential to foster the emergence of such questions and their in-depth exploration.

5) *The fifth type of questions are the ordinary questions that are technical questions related to prior knowledge.*

Such questions are relatively rare among students in the experimental group, while a lot were found in the control group. This may be due to the 7E IBL model, which has established a solid knowledge system for students, resulting in fewer questions arising from forgetting prior knowledge in the experimental group classrooms. The explanation for this finding will be one of the key points discussed in the Discussion Chapter.

In summary, the findings showed clear distinctions between the experimental and control groups in both the number and nature of questions raised during lessons. Students in the experimental group asked significantly more questions, with an average of "eight to ten" per lesson, compared with "three to four" in the control group (Teacher A and B). More importantly, the questions in the experimental group demonstrated greater cognitive depth, shifting from technical or recall-based queries to those that involved reasoning, knowledge extension, and problem-solving. In contrast, "questions from the control group largely centred on procedural or previously taught content" (Teacher D). Beyond the numerical difference, the findings also suggest that the use of the 7E IBL model encouraged students to engage in higher-order thinking and to take on a more active role in their own learning with confidence. The gradual transformation from asking surface-level questions to generating complex, exploratory ones indicates that the intervention not only enhanced students' questioning ability but also fostered

the development of CT. At a deeper level, this change reflects a shift in students' epistemic stance, which is from passive receivers of information to independent thinkers capable of inquiry, reflection, and knowledge construction.

7.2. Students' performance and classroom atmosphere

7.2.1. In discussion section

In the experimental group, due to the targeted cultivation of CT skills and dispositions in classroom teaching, as well as the ample time and opportunities provided for students to think and practise, their CT improved dramatically, contributing to a more dynamic classroom atmosphere. However, neither teachers nor students were familiar with the new model's classroom organisation at the start of the semester. Students felt uncertain during open exploratory discussions because of this unfamiliarity. They frequently found it difficult to properly express their enquiries and lacked the capacity for in-depth dialogue and investigation. Teachers also encountered challenges in guiding students through these explorations. As the semester progressed, through continuous dialogue and adjustments between teachers and researchers (a process that lasted for an entire month) teachers gradually developed a deeper understanding of the new model, and classroom instruction began to stabilise. Students learned how to ask questions and collaborate with their group members, stimulating more intellectual exchanges and further energising the classroom atmosphere. Under the guidance of the new model, students' enthusiasm for learning increased a lot, and classroom discussions became more active, particularly in STEAM subjects with a stronger emphasis on science and mathematics.

Furthermore, students' dependence on professors diminished as they progressively adjusted to the 7E IBL model, and they no longer needed as much outside encouragement. Teachers also observed that students in the experimental group became more independent in problem-solving as the intervention progressed. Rather than immediately turning to their teachers for assistance, they tended to engage in group discussions or conduct independent research to identify and test possible solutions. As one teacher explained:

They became more willing to solve difficult problems by themselves instead of asking the teacher about everything. I think this is very positive. Students in both classes

communicated with each other, but in the experimental group, they often shared techniques within their small groups and managed to resolve the problem on their own. The questions they asked were usually more specific and challenging, only when they really could not find a solution would they ask the teacher. In contrast, students in the control class tended to ask about everything before they even started working, showing less confidence in solving problems independently. (Teacher D)

More encouragingly, students showed an increased ability to understand and solve problems on their own during the learning process. This illustrates that the 7E IBL model fostered greater learner autonomy and confidence, enabling students to approach challenges collaboratively and critically before relying on teacher guidance, a key indicator of developing CT. This change from passive reception to active investigation offers strong proof that the pedagogical intervention was successful in helping students develop their capacity for independent learning. Students in the control group, on the other hand, kept using the conventional learning approach. Since the classroom design lacked explicit training in CT skills, the limited discussion activities saw low engagement, and the overall classroom atmosphere remained relatively passive. There was little evidence of deep disciplinary thinking or innovative discussions. Teachers widely reported that improvement in CT among students in the control group was not apparent. This stagnation in CT development was closely linked to the absence of corresponding instructional strategies in the curriculum design.

Overall, during discussion sessions, students in the experimental group were provided more time and opportunities for reflection and discussion under the new instructional model. They also received targeted training in applying CT to inquiry and learning, which directly contributed to their improvement in CT. After a semester of study, they progressively understood the fundamental ideas of CT and its real-world applications, despite the fact that their first performance seemed a little rough. Students gained confidence and started participating more actively in class discussions with their peers under the direction and support of their teachers. An intellectually stimulating environment raised students' interest in learning and boosted their involvement with the course, which was directly promoted by this learning paradigm. Eighty percent of students said that the discussion periods were their favourite aspect of the class, according to a small-scale, random-sampling questionnaire that was used during

the intervention study. They observed that learning was more pleasurable under the new paradigm as the classroom experience differed significantly from typical lessons in other disciplines. Additionally, the Q&A segment following the presentation section was equally well received, as students appreciated the freedom to ask questions and engage in discussions. Students in the control group, on the other hand, reported a more passive classroom environment and lower levels of engagement since they were not given the chance to engage in open conversation or peer interaction. The overall classroom dynamics were noticeably less vibrant than in the experimental group. According to teachers' observations, there was no evident improvement in the control group students' CT skills or dispositions.

7.2.2. In the extension section

Within the 7E IBL model, the final stage of the instructional process is the *Extension* phase. In this stage, the teacher utilises the *Notebook* as a pedagogical tool to systematically guide students in reviewing and synthesising key concepts and essential knowledge covered in the lesson. Through well-crafted learning activities, students are encouraged to apply their recently acquired discipline knowledge to real-life circumstances after this first consolidation. More precisely, by encouraging students to create open-ended issue scenarios and accompanying solutions, the instructor supports this process. For instance, a teacher used the following example to inspire students' inquiry:

Today, we have explored how to design watch faces using specialised software. *Have you considered extending this skill to other aspects of everyday product design?* You might, for example, experiment with customising phone cases, home décor items, or even user interfaces for smart home devices. (Teacher C)

Given classroom time constraints, this phase primarily emphasises the plan of the design rather than producing a real product. With its primary goal being to develop students' capacity to transfer and apply basic disciplinary principles rather than only looking for a standardised answer to a particular problem, this educational method supports the idea that the learning process should take precedence over definitive conclusions. Therefore, students in the experimental group's ability to learn on their own and transfer knowledge is best shown during the *Extension* phase. Additionally, in order to finish the mini tasks in the Notebook, students

must actively engage their CT. The following sections will provide further detail on the investigation's specific findings on the Notebook.

During the *Extension* phase at the conclusion of sessions, teachers noticed that students in the experimental group generally showed a high motivation to participate in independent inquiry. For example, "students had heated debates over the fundamental scientific ideas of solar power during a lesson examining the use of solar energy in drones. After class, 2 girls approached me and asked if it would be possible to incorporate drone technology into self-driving cars" (Teacher C), showing their curiosity outside of the classroom. They shared early concepts created in partnership with their group members, showcasing their desire to help make autonomous driving technology a reality. A further example of this can be found in a lesson focused on wood carving techniques and the craftsmanship of Filipino keychain production. Students in the experimental group raised a commercially oriented question: "*Is it possible to develop products using wood carving or keychain-making techniques and bring them to market?*" (Teacher C). Such questions represent the growth of higher-order thinking abilities and provide an example of application to the real world. Students' questioning habits, which combine craftsmanship and business reasoning, offer strong proof of their notable development in all-around cognitive skills. More specifically, when students posed this question during the *Extension* phase, they had, in fact, already engaged in multiple layers of CT. First, they needed to fully comprehend and master the core technical aspects of wood carving and keychain production. Next, they were required to recognise the potential market value of these traditional crafts. Finally, they had to consider how techniques could transform into commercially viable products. This progression (from technical understanding to market analysis) exemplifies their capacity for CT. Moreover, the tendency of students to raise those extension questions is noteworthy. They showed a stronger desire to investigate the real-world and possible worth of the learnt knowledge rather than asking questions about technical specifics. This change shows that students were actively weighing the information's practical implications rather than passively receiving it, which is a crucial sign of improved CT. Such an advancement is evident in their ability to pose more sophisticated questions and the qualitative transformation of their perspectives and analytical approaches.

In conclusion, the *Extension* step created a more focused and dynamic classroom atmosphere, and students are strongly engaged and independent in discussions. Compared to the control

group, those in the experimental group remained attentive during the teacher's review of subject content and took an active role in the subsequent near-transfer tasks (Teacher D). They asked exploratory, thought-provoking questions and attempted to apply their new knowledge to unfamiliar situations. Teachers also noted that "these students sustained their concentration until the end of the lesson" (Teacher D). In contrast, the control group, without a structured *Extension* phase, often showed "signs of distraction in the later part of the class, with less focus and weaker awareness of learning goals" (Teacher D).

The questions raised by the experimental group further illustrated a deeper level of inquiry, drawing on knowledge integration and application rather than staying at surface understanding. These observations suggest that the *Extension* phase not only stimulated students' interest in learning but also supported their ability to maintain focus. This provided a strong basis for developing new inquiry scenarios and project plans. In doing so, students became more naturally engaged in transferring and applying knowledge, while at the same time strengthening their CT.

7.3. Students' mastery of subject knowledge

Under the 7E IBL model, students gradually construct a solid disciplinary knowledge system through a structured learning process in each lesson, one that encompasses reviewing previously acquired knowledge, engaging in inquiry-based exploration of new subject matters, and reinforcing their understanding through repeated application and reflection. This progressive approach enables students to consolidate foundational knowledge and deepens their comprehension and internalisation of subject matter. As a result, both students and teachers can more clearly assess learners' grasp of each lesson's content, identifying areas of strength as well as aspects that require further reinforcement or additional learning. According to teachers' observations, students in the experimental group were able to internalise subject knowledge acquired through IBL while also developing proficiency in technical aspects, such as the functional modules of software and their corresponding operational procedures. This was reflected in the clear decline of routine or surface-level questions during classroom discussions. Such progress can be linked to the structured design of the 7E IBL model, where teachers regularly followed knowledge explanations with guiding questions. So, the 7E IBL model strategy encouraged students to refine their understanding and reinforce memory retention

through problem-solving during independent inquiry.

I think students in the experimental group asked fewer questions because they were more proactive in solving problems on their own while the control group relied more on teachers. The students in the experimental group have Notebook, like a learning journal, where they marked down key points or drew diagrams. This helped them remember important content, so they didn't need to ask as many questions; they could use those notes and skills to think things through independently. (Teacher D)

A key advantage of this instructional design is that even in educational settings where STEAM courses are not core subjects and are offered with relatively low frequency, such as participant school, where each class receives only one STEAM lesson every two weeks, students can still retain knowledge effectively between sessions. Although when minor details are forgotten, they can quickly retrieve information by consulting the knowledge summary section in their Notebook. Additionally, at the start of each lesson, teachers spend two to three minutes reviewing previously covered material. This regular practice helps students who participate actively to consolidate their learning, making it less likely for them to forget. Through this mechanism, a positive learning cycle was gradually established, facilitating both knowledge construction and long-term retention as the course progressed. Meanwhile, the emphasis on a sequential and cohesive instructional model is particularly well-suited to long-term learning processes, especially within semester- or year-long teaching cycles where subject knowledge exhibits strong continuity. In STEAM education, long-term curricula are marked by strong internal coherence, as new knowledge often builds on and extends what students have already learned rather than standing as isolated concepts. Because of this disciplinary structure, ensuring continuity in instruction is especially important. Consequently, adopting a gradual, progressive approach to constructing a structured knowledge system emerges as a fundamental pedagogical strategy in the 7E IBL model.

Moreover, students in the experimental group posed fewer questions related to prior knowledge during inquiry activities, which helps reduce the time teachers need to revisit previously covered material (Teacher D). As a result, students were able to devote more time to inquiry-based tasks, which partly alleviated the challenge of limited class time (a fuller discussion of time allocation appears in a later section). In this way, the refinement of the new instructional

model not only improved teaching quality but also allowed teachers to focus more on introducing new knowledge and guiding inquiry activities. The change in students' questioning patterns also offered teachers useful feedback on students' comprehension. With this information, teachers could "adjust the pace of instruction, slowing down for more difficult concepts and moving more quickly through material that students understood with ease" (Teacher D), thereby enabling more targeted teaching strategies tailored to different classes. However, the control group showed a different pattern as students often forgot basic information in the two weeks between lessons, " teachers had to spend a large amount of class time answering questions related to prior knowledge" (Teacher D). Their capacity to engage in inquiry-based activities was hindered by this persistent problem. Over time, it not only undermined students' self-esteem but also strengthened a passive learning style characterised by a strong reliance on teacher direction. Teacher D noted that "students in the control group frequently had trouble understanding new material" (Teacher D). This difficulty was attributed to both general deficiencies in independent thinking and self-directed learning practices as well as gaps in information retention.

In addition to the above two main reasons identified by teachers, researcher believed that an additional factor could be students' underdeveloped CT. A lack of competence in CT directly undermines their capacity for independent reasoning and results in fragmented retention of knowledge. This issue will be analysed in greater depth in the discussion chapter, where relevant theories will be used to provide a more comprehensive explanation. Moreover, once students in the control group begin to develop learning habits that do not support systematic knowledge construction, they find it increasingly difficult to allocate time for targeted training in specific skills such as CT. These deficiencies may not immediately produce visible setbacks or dramatic regression in the short term. However, when compared with the experimental group, they were less competitive in terms of learning outcomes, both knowledge retention and the cultivation of higher-order thinking skills.

In summary, based on teachers' feedback, students in the experimental group demonstrated a markedly higher level of mastery of classroom knowledge compared to those in the control group. This is because the 7E IBL, as an integrated model, has a central feature, which is a recursive mechanism that allows students to revisit and reapply subject knowledge at multiple

points in the learning process. Combined with the near-transfer tasks embedded across its stages, this mechanism promotes a continuous cognitive cycle that strengthens understanding and supports the application of key disciplinary concepts. At the same time, the use of this instructional model has brought notable pedagogical advantages. Not only has it contributed to an overall improvement in teaching quality, but it has also enabled teachers to allocate more time to introducing new knowledge and facilitating students' independent construction of disciplinary understanding. The following chapters will present a more detailed discussion of how 7E IBL model has influenced teachers' instructional practices and students' CT.

7.4. Notebook in the extension step

The initial development of the Notebook was from the need to optimise students' learning approaches within the classroom. The researcher aimed to create a tool that would help students systematically record and reflect on their learning process and encourage active engagement with knowledge rather than passive reception. The Notebook is designed as a pedagogical support tool specifically for the final stage of the 7E IBL model, (the *Extension* phase) it consists of two core components: a structured summary of classroom knowledge and mini tasks, each corresponding to the two instructional steps, summary and knowledge extension. First, teachers guide students in systematically reviewing and synthesising the subject matters covered in the lesson. Second, they introduce real-life scenarios, encouraging students to reapply and extend their learning by devising solutions to new problems. For instance, after completing all instructional content, the teacher might pose an extension question in a lesson on laser cutting technology: “*Now that you have mastered this technique, beyond the clock face design we have already completed, what other items do you plan to create?* Please discuss in pairs or groups and develop a detailed project proposal”. This instructional design reinforces students' understanding of technical principles and fosters their ability to transfer knowledge and cultivate innovative thinking.

Compared to traditional classroom notes, the Notebook is more structured and task-oriented. Incorporating mini tasks ensures that they function as a recording tool and a medium for organising thought and constructing knowledge. In practice, all of the participating teachers have expressed positive feedback regarding Notebook's implementation, recognising its effectiveness in supporting instruction and enhancing students' learning experiences to a

certain extent. According to the participating teachers' interview, there are two key dimensions: first, teachers' overall evaluation of the Notebook as an instructional aid and its pedagogical value; second, the extent of students' engagement with the Notebook and the potential factors influencing their completion of the tasks.

- Teachers' overall view on the notebook

Firstly, teachers unanimously agreed on the Notebook as a necessary part in helping students consolidate their knowledge. It provides learners with a systematic summary of their learning, enabling them to gain a more intuitive understanding of their learning progress. In the past, students might have only written down notes in other subjects, such as mathematics, English literacy, and chemistry lessons. However, when it came to STEAM education, it was rare for them to take notes at all during the lesson, as claimed by their teachers. This often led to a disjointed understanding, making it difficult for learners to form a coherent knowledge network. However, through its task-driven approach, the Notebook encourages students to organise and summarise their knowledge throughout the learning process actively. More importantly, teachers encourage students to supplement their understanding at any point during their exploration, transforming the Notebook into a dynamic learning tool rather than just reusing classroom content.

I think students would have a clearer understanding of what they have learned and what they have not in each lesson. The notebook is helpful for them because if they have a tool with a summary after every class, they can better recognise their level of progress and manage their learning process more effectively. (Teacher B)

Because students had Notebooks to record their learning progress, some students would write down their reflective questions in them. For example, they noted areas where their designs could be improved or what unique features they had. In the classes without this notebook, students missed the time for consolidating and digesting knowledge. I think this Notebook and the way it is used can help students develop a more comprehensive understanding of the lesson. (Teacher A)

Additionally, the Notebook's visual nature is another aspect that makes it highly appreciated by teachers. In the mini-task sessions, compared to traditional classroom questioning methods,

students were often limited to internalising their thoughts when faced with a question from the teacher. It allows learners to visualise their thinking by writing it down, as teachers also encourage them to use different methods, such as mind maps or keywords, to highlight the main subject knowledge they have learned. This "visual thinking" not only aids students in organising their thoughts more clearly but also enables teachers to understand students' thought processes better, thus offering more targeted guidance. Therefore, the Notebook encourages students to write down their ideas, rather than merely engaging in chaotic reasoning in their minds.

Previously, we didn't have notebooks, but now students can record the trajectory of their thinking in class. In the past, when they were asked to complete a task, they could only think through it in their heads. Now they can visualise their thoughts by writing them down on paper and keep track of how their ideas develop. For example, in the first lesson, their thinking might be like this, but by the second lesson, they might realise that some of their ideas have changed. So, I think the notebook is actually very beneficial for their learning. (Teacher B)

Teachers also pointed out that the Notebook can be a useful tool for boosting student involvement in the classroom. Teachers and students often communicate in the classroom using a question-and-answer style, but the Notebook gives students more opportunities to talk with one another as " they worked on the notebook as a group, which allowed students to share more with one another" (Teacher D). In order to promote collaborative learning and enhance class discussions, teachers can, for instance, encourage students to express their thoughts on the Notebook and exchange differing points of view, making them more varied and complex. Additionally, for students who are less inclined to speak up in class, the Notebook provides an alternative means of expression, allowing them to present their thoughts in written form without the pressure of direct verbal communication.

Finally, the Notebook has, to some extent, contributed to enhancing students' ability to learn in a self-directed manner. In order to arrange their information, identify areas of doubt, and bring queries to the following session for clarification, some students utilise the Notebook outside of class, according to teachers. Students can focus on applying their information in wider situations in addition to their in-class learning thanks to this process of self-recording and

reflection, which helps them develop stronger learning habits. Although such occurrences are relatively rare, over time, the frequency of this will show a positive upward trend.

- The completion of the notebook

However, despite the numerous advantages of the Notebook from the teachers' perspective, students' actual completion of the mini-tasks section in Notebook was far from ideal. An analysis of the collected Notebook samples revealed that, while there were some well-developed and content-rich examples, more than half of the Notebooks were either overly simplistic in their responses or left entirely blank. The researcher identified several key factors contributing to this phenomenon through in-depth interviews with teachers.

Firstly, since most tasks were completed in groups, it was common for multiple students to share a single Notebook (Teacher D), which often led to some blank notebooks. A small percentage of students misplaced their notebooks, which teachers saw as an indication that they were not interested in the subject (Teacher C). Furthermore, because the Notebook was mostly finished in class, some students found it difficult to finish their entries on time due to the strict scheduling of some lessons and the lack of homework. Hence, teachers believed that the initial design of the Notebook required further optimisation, for example, reducing the proportion of open-ended questions and incorporating more structured task formats, such as fill-in-the-blank exercises (Teacher D). Finally, the most influential underlying factor was tied to broader educational policies. Since STEAM education was not part of the university entrance examinations, students in high-performing schools such as the participating school faced heavy academic pressure and were compelled to devote most of their time and energy to exam-related subjects. As a result, enthusiasm for STEAM education was generally low, and some students were unwilling to put in extra effort outside of class. From teachers' perspective, they recognised the pressures students were under and were therefore hesitant to impose additional demands or assign more homework, as they did not wish to add to an already overwhelming workload. One teacher explained, "I don't want to pressure my students too much. After all, I would rather they enjoy the process and find some relaxation in class through STEAM education" (Teacher B). It shows that the teachers' attempts to balance curriculum goals with the realities of students' academic burden, which in turn contributed to the lower completion

rates of the Notebooks. Nevertheless, as some teachers noted, improvements could still be made, such as refining the design of the Notebook to enhance its effectiveness.

Overall, teachers expressed positive attitudes toward using the Notebook in STEAM education classroom teaching to their students, acknowledging its value in four main areas: structuring knowledge systematically, visualising cognitive processes, enhancing classroom interaction, and fostering independent learning. From a research perspective, the Notebook is not simply a classroom aid but an important medium for supporting long-term knowledge construction and deep learning, which may explain why it was widely endorsed by teachers in the intervention project. However, the data show that students' completion of the mini tasks in the Notebook was less than satisfactory. A key reason for this is that STEAM education is not part of the university entrance examinations, which led both students and teachers to prioritise exam-related subjects over STEAM courses. As a result, some students placed limited emphasis on the course, and teachers subsequently lowered their expectations for student engagement with the Notebook. Although the challenges still exist, there are several strategies that could be adopted to help students complete the Notebook. One option is to optimise its design by reformatting some open-ended questions into more structured tasks, such as fill-in-the-blank exercises, to provide clearer guidance. In addition, teachers could encourage students to pay more attention to the Notebook from the beginning of the STEAM education course; in this way, it may help students build stronger habits of engagement. The results indicate that, with careful modifications, the Notebook can remain a crucial component of the 7E IBL model and continue to be a useful and successful teaching tool.

8. Discussion

This section will address the three research questions (see below), drawing on findings from both the qualitative and quantitative analyses. It will begin with a summary of the results, followed by a discussion of the potential reasons behind these outcomes, incorporating relevant theoretical perspectives from the literature review. Particular focus will be placed on the pedagogical links between the 7E IBL model and students' CT (including both skills and dispositions). The discussion will then explore examine possible reasons for the slower development of CT skills, how the 7E IBL model may have contributed to improvements in students' CT and consider the pedagogical implications for sustaining the model. Finally, other factors influencing students' CT development through the 7E IBL model, such as teacher enactment, will also be discussed.

- **To what extent does an intervention use the 7E IBL framework in STEAM education influence secondary students' CT dispositions?**
- **To what extent does an intervention use the 7E IBL framework in STEM education influence secondary students' CT skills?**
- **Is there a correlation between the impact of CT disposition and skills in STEM education?**

8.1. Summary of findings from qualitative and quantitative analyses

The integration of qualitative and quantitative analyses provides a comprehensive understanding of the impact of the new instructional model on students' CT skills and disposition, and which is set out in Table 49:

Metrics	Changes (Experimental groups)	Changes (control group)	Metrics	Changes (Experimental groups)	Changes (control group)
CT Skills overall	+	-	CT Dispositions overall	+++	-
Analysis	+++	-	Truth-seeking	+	-
Inference	+	-	Open-mindedness	+++	-
Evaluation	++	+	Analyticity	+++	-
Induction	+	+	Systematicity	+	+
Deduction	++	-	Confidence in Reasoning	+++	-
Interpretation	++	+	Curiosity	-	-
Explanation	+	+	Cognitive Maturity	+++	+
Numeracy	+++	+			

(significant increase: +++; potential significant increase: ++; increase: +; decrease: -; no change: =)

Table 49: Summary of changes in students' CT skills and dispositions after intervention

8.1.1. The impact on CT disposition

Both qualitative and quantitative data consistently indicate a notable improvement in students' CT dispositions. The experimental group students demonstrated a stronger inclination towards inquiry and independent thinking, as observed by teachers and confirmed through quantitative assessments. Teacher interviews highlighted increased student engagement, proactive questioning, and enthusiasm for discussion, reinforcing the quantitative findings that showed a notable rise in CT disposition scores.

8.1.2. The impact on CT skills

While the quantitative data on CT skills did not reveal a statistically significant overall improvement, the post-test results of students in the experimental group showed varying levels of improvement across all eight CT skill metrics, whereas the control group showed slight improvement in half of the metrics, with one remaining stable and three showing a downward trend. Because of the nature of quantitative analysis, which relies on pre- and post-test comparisons based on the average scores of all students, it only allows for an assessment of overall trends. However, qualitative observations of the impact on CT skills provided a more nuanced perspective. Teacher interviews offered important supplementary insights, indicating that although not all students exhibited significant improvement in CT skills, there were cases where students showed noticeable gains in their performance, whereas no comparable improvement was observed in the control group. Teachers reported that, in the experimental groups, some students exhibited substantial gains in their ability to use CT skills. This qualitative insight supplements the quantitative results. The reliance on mean scores in the quantitative analysis masked the progress made by certain students, suggesting that while the instructional model had a limited effect on enhancing CT skills across the entire group, it was highly effective for some individuals.

Overall, the findings highlight that the 7E IBL model had a positive impact on both students' CT skills and dispositions. In particular, it produced a statistically significant improvement in CT dispositions, although there remains room for further enhancement in improving their CT skills scores. Encouragingly, both the positive trends observed in quantitative data and the qualitative feedback from teacher interviews suggest that the 7E IBL model has already begun

to show progress in the short term for students' CT skills. While it may not yet represent the "optimal outcome," it undoubtedly marks a hopeful and valuable beginning.

8.1.3. Correlation between CT skills and dispositions

According to the statistical analysis of quantitative data, there was no correlation between students' CT skills and dispositions in secondary school. In other words, possessing a high level of CT skills does not necessarily imply a strong inclination to apply these skills proactively. Likewise, a strong CT disposition does not reliably predict a student's actual CT skills in practice.

8.2. Factors influencing students' CT changes through the 7E IBL model

In this section, the researcher will use both quantitative and qualitative data and adopt a theoretical lens exploring how the 7E IBL model enhances students' CT regarding their skills and dispositions. Data from students in the experimental group has already shown the model's potential in promoting CT development. To examine this further, data from the control group will be used to understand better the limitations and influencing factors that may hinder such development in traditional settings. the researcher will first systematically analyse the links between CT and the 7E IBL model, along with the underlying contributing factors. This will be followed by an explanation of the diverging outcomes found. First, although CT skills showed emerging positive trends across dimensions, they did not reach statistical significance overall; the discussion will explore the possible influencing factors, limitations, the insights and recommendations derived from the findings. Second, particular attention will be given to examining the mechanisms through which the 7E IBL model significantly enhanced students' CT dispositions within a relatively short intervention period, highlighting the key pedagogical implications of this outcome. In addition, other impacts like the way teachers guided and supported students during lessons will also be examined, as their role appears to play an important part in facilitating students' CT in practice.

8.2.1. Pedagogical link between the 7E IBL model and students' CT

In a recent systematic review, researchers examined 25 studies published between 2000 and 2024, all of which consistently demonstrated the positive impact of IBL on students' CT skills (Arifin et al., 2025). At the same time, a growing number of research studies explored the relationship between IBL and CT disposition. In this project, the 7E IBL model, grounded in the principles of IBL, provided empirical evidence of its effectiveness in enhancing both CT skills and dispositions. Notably, the intervention group showed statistically significant improvement in CT disposition scores. The main reason behind this outcome lies in the strong alignment between the pedagogical features of IBL and the essential conditions for developing CT. In other words, IBL not only supports students' higher-order cognitive growth but also fosters their emotional engagement and motivational commitment to CT as a long-term practice (Hmelo-Silver et al., 2007). As illustrated in the two tables presented below, students received targeted support and development across various dimensions of both CT skills and disposition throughout different stages of the 7E IBL model. Although the overall quantitative results for CT skills did not show a significant leap following the intervention, all eight sub-dimensions exhibited varying degrees of improvement. This achievement can be attributed to the 7E IBL model's instructional design, which systematically activates and reinforces diverse aspects of CT skills across the learning process. Below, the researcher will systematically examine how each phase of the 7E IBL model corresponds to the key developmental needs of CT, highlighting the 7E IBL model's distinctive value in cultivating sustained CT attitudes.

8.2.1.1. CT Skills & 7E IBL model

CT skill developed	7E IBL model phase	Student tasks
1. Analysis	Prepare, Inquiry	Analyse topic to select suitable inquiry tasks. Identify key problems.
2. Inference	Inquiry, Presentation	Predict logical steps in inquiry through reasoning.
3. Evaluation	Inquiry, Presentation, Extension	Evaluate each inference. Assess peers' arguments in Q&A. Re-evaluate own conclusions.
4. Induction	Inquiry	Carefully generalise from initial findings during group work.
5. Deduction	Inquiry, Extension	Apply logical deduction to synthesised conclusions.
6. Interpretation	Presentation, Extension	Explain relevance of conclusions in context and new scenarios.
7. Explanation	Inquiry, Presentation, Extension	Justify conclusions with evidence in discussions, Q&A, and new scenarios.
8. Numeracy	Inquiry	Use quantitative reasoning during inquiry tasks.

Table 50: Linke between CT skills to the 7E IBL model with corresponding student tasks.

Interpreting the 7E IBL column in the Table 50, it is seen that during the **Preparation** stage which including **Elicit** and **Design** steps, students are required to apply their analysis skills to identify core issues worth exploring in relation to the classroom topic. In the **Inquiry** phase, this happens quite a lot in different typically carried out in small groups, students must pinpoint key components of the problem, demanding precise *analytical* thinking in complex contexts. They then use *inference* to anticipate the direction and steps of their investigation, while evaluation is employed to assess the validity and soundness of each inference. Meanwhile, *explanation* supports the construction of clear and coherent conclusions. When facing multiple arguments, students integrate fragmented information using *induction* and construct logically supported judgments through *deduction*; *interpretation* and *explanation* continue to assist them in articulating the significance of each judgment within the given context. At the same time, tasks involving quantitative analysis embedded in the inquiry process help develop their *numeracy*.

There are several opportunities in the 7E IBL model, particularly during the **Presentation** phase. This phase involves group presentations and Q&A sessions, which not only enhance students' ability to express and defend their viewpoints, but also encourage their peers to engage in evaluation by critiquing others' arguments and asking in-depth questions. In turn, speakers must again employ *interpretation* and *explanation* to respond effectively, promoting a cyclical and authentic use of CT skills through real-time interaction, during the **Extension** phase, students are asked to formulate transferable problems in new contexts and devise solution plans grounded in their existing knowledge base, once again systematically activating and integrating a wide range of CT skills, such as evaluation and explanations.

It is worth reiterating that despite the limited intervention period in this project, students were afforded meaningful practice across all dimensions of CT skills step by step. However, as a complex and advanced cognitive process, the true development of CT skills requires more time, greater intensity, and repeated opportunities for application and refinement. Encouragingly, both the positive trends observed in quantitative data and the qualitative feedback from teacher interviews suggest that the 7E IBL model has already begun to show progress in the short term. While it may not yet represent the “optimal outcome,” it undoubtedly marks a hopeful and valuable beginning.

8.2.1.2. CT dispositions & 7E IBL model

CT Dispositions	7E IBL Model phase	How Model Influences Students' CT Dispositions
1. Truth-seeking	Inquiry, Extension	Persistent pursuit of evidence-based answers to contextual problems during inquiry and extension.
2. Open-mindedness	Design, Inquiry, Presentation, Extension	Group work fosters diverse perspectives; Q&A and near-transfer tasks encourage exploration from multiple angles with an open mindset.
3. Analyticity	Inquiry, Extension	Prediction and analysis of outcomes during inquiry; near-transfer tasks in extension involve planning and analytical thinking.
4. Systematicity	Inquiry, Extension	Complex topics are broken down and addressed step by step in a structured, logical manner throughout the inquiry process.
5. Confidence in Reasoning	Elicit, Inquiry, Presentation, Extension	Prior knowledge review builds a solid foundation, reducing confusion and boosting confidence. Ongoing success, peer and teacher affirmation, and knowledge reuse in extension reinforce self-efficacy.
6. Curiosity	Design, Inquiry, Presentation, Extension	Student-designed learning paths, exploratory inquiry, frequent opportunities to ask questions, and engagement in transfer tasks keep students curious and motivated.
7. Cognitive Maturity	Elicit, Presentation, Extension	Prior knowledge integration in elicit stage strengthens conceptual understanding; Q&A and self-evaluation in extension promote thoughtful, timely decision-making.

Table 51: Linke between CT skills to the 7E IBL model with how model influence students' CT dispositions.

Similarly, as shown in Table 51, the 7E IBL model has demonstrated a significant positive impact on the development of students' CT dispositions, a result attributable primarily to the model's sustained reinforcement and repeated engagement with the seven measured dimensions of disposition across its various stages. For instance, in the **Elicit** stage, teachers guide students to revisit their prior knowledge, an activity that not only aids in the consolidation of understanding but also, over time, contributes to the implicit construction of a more integrated knowledge system. When paired with the active integration and transfer tasks in the

Extend phase, this continuous linkage between the old and the new enhances students' *Cognitive Maturity* and provides them with greater direction and control in subsequent inquiry, thereby reducing feelings of confusion and frustration. This positive learning experience, in turn, fosters students' *Confidence in Reasoning*, as they become more willing to trust their own judgement and persist in rational analysis when confronted with complex problems.

Moreover, during the **Inquiry** phase, the structured design of the 7E IBL model systematically triggers and strengthens several core dimensions of CT disposition. When faced with context-based problems, teachers adopt an open and encouraging stance that motivates students to explore real-world issues. This process not only activates their intrinsic *Truth-seeking* drive but also helps them cultivate a sustained commitment to the pursuit of truth. In collaborative group settings, students practise perspective-taking by listening and responding to their peers' viewpoints, gradually developing a more open and inclusive mindset, an essential manifestation of *Open-mindedness*. Throughout the entire **Inquiry** process, students engage in continuous *Analyticity* through their efforts to analyse, hypothesise, and predict based on emerging ideas. Their ability to deconstruct complex issues into manageable steps and advance solution plans reinforces their systematicity.

Another noteworthy strength of the 7E IBL model lies in its natural elicitation and maintenance of *Curiosity*. When students are encouraged to select their own learning topics, pose questions, and engage in problem-solving, they remain in a state of active inquiry and exploration. For example, the **Presentation** stage, particularly the Q&A exchanges, provides not only opportunities for students to express their ideas but also authentic moments in which *Curiosity*, CT, and communication skills are vividly demonstrated. In the culminating **Extend** phase, students are required to generate near-transfer problems and design novel solution plans, an endeavour that encourages them to examine how existing skills might transfer across contexts while simultaneously stimulating their *Curiosity* and *Analyticity*.

Most importantly, as students begin to see progress throughout the inquiry process, the affirmation they receive from teachers and peers, particularly during the **Inquiry** and **Presentation** phases, as well as the immediate feedback resulting from reapplying knowledge in the **Extend** stage further strengthens their sense of *Confidence in Reasoning* and *Curiosity*.

This real-time positive feedback mechanism not only enhances the learning experience itself but also lays a solid psychological foundation for the continued development of CT disposition. In other words, while the 7E IBL model supports students' *Cognitive* development, it also responds meaningfully to the affective and attitudinal dimensions essential to fostering a strong disposition towards CT.

8.2.2. Possible reasons and improvement strategies for the changes in CT skills

The results from the quantitative data, particularly the average scores from the CT skills test, showed that there was limited change in the experimental group's performance before and after the intervention. Although an improvement could be observed, it was not statistically significant. However, the qualitative data painted a different picture. According to the teachers' observations, a small portion of students (approximately 1 out of 5 students per class, around 5/6 students in one class/30 students) in the experimental group showed noticeable progress in their CT skills performance. The slow development on overall CT skills and individual breakthroughs suggests the new model's limitations in boosting students' CT skills across the board. Through analysis, the researcher identified several possible explanations below. Beyond the fact that the model itself may still need further refinement, the results could also be linked to the delayed nature of CT skills development and the limited duration of the intervention. These factors might have influenced the overall outcome and should be considered when evaluating the model's impact.

To better understand the potential limitations in students' development of CT skills, the researcher examined the specific indicators commonly used to assess such development. According to the literature review, several learning approaches have been consistently shown to improve students' CT skills. These include IBL, collaborative learning, class discussions, debates, case-based learning, Socratic questioning, and discovery learning. The 7E IBL model used in this study incorporates nearly all of these elements, and it was intentionally designed to strongly emphasise the development of students' CT. In theory, this should have led to noticeable progress. However, while the test results in CT skills showed some improvement, the gains were not statistically significant. Several possible explanations may account for this outcome and the improvement strategies are discussed in detail below.

- a) The intervention intensity is insufficient. A possible solution is to improve the model, with a particular emphasis on strengthening teachers' guiding and enhancing students' collaboration, discussion, and debate during the inquiry process.
- b) Students and teachers need time to adapt to and grow within the new teaching model.
- c) Improving CT skills requires long-term cultivation. The duration of the intervention is not long enough. It is suggested that the intervention period be extended to improve the stability and significance of the effects.

a) *Insufficient intervention intensity*

The intensity of the intervention may not have been strong enough. While the model itself covers many components that are known to support CT skills, such as IBL, teacher-guided questioning, group discussions, and peer collaboration, these elements may not have been emphasised enough in actual classroom practice. Further improvements to the model could involve placing more focus on teacher-led questioning that encourages deeper thinking, and strengthening the roles of debate, cooperative inquiry, and group reflection during the learning process.

As pointed out by Darling-Hammond et al. (2017), to support learners in engaging more effectively in inquiry learning, it is necessary to establish an environment, structure, and set of practices that respond to students' developmental needs, which is not merely a matter of improving instructional strategies but also includes providing students with a supportive and coherent learning environment. In this project, at the school level, such support can be reflected in a reasonably structured and continuous curriculum arrangement, which aims to minimise fragmentation between courses while also building trust between teachers and students, factors that together help to create a safe and stable learning atmosphere, enabling students to engage in inquiry activities with greater ease and focus. However, the participant school's STEM curriculum arrangement, with an interval of more than two weeks between sessions, to some extent undermines the continuity of learning and may affect students' concentration and depth of inquiry. Therefore, a possible adjustment could be to change the current arrangement of one 90-minute session every two weeks into one 45-minute session per week. In this way, while keeping the total instructional time unchanged, the learning experience could become more continuous and frequent, helping students maintain the flow and continuity of their thinking and cognitive engagement.

Regarding the instructional strategies, several aspects still require further refinement and improvement. These include whether the choice of topics is appealing and relevant, whether the inquiry process is sufficiently rich, whether the teacher's guidance and support during group collaboration are in place, and whether students receive timely and effective assessment and feedback, all of which are crucial for promoting students' metacognitive development and the cultivation of CT. Although these elements are also required in various stages of the 7E IBL model, the unsatisfactory test results suggest that each stage still has room for optimisation and enhancement to achieve the model's intended outcomes more effectively. Therefore, the researcher will enrich the user guide for the model, which will be presented in the 9.5.2. Practical implications. The aim is to provide more guidance to users on how to implement the model in actual classroom settings.

b) The importance of preparatory work before the intervention: allowing sufficient time for students and teachers to adapt and grow under the new teaching model

Both teachers and students need a certain amount of time to adjust and gradually adapt their teaching and learning approaches when faced with a new instructional model. Switching from more traditional approaches to a structured inquiry-based model requires not only a change in teaching techniques but also a shift in classroom mindset. This process of adaptation, in and of itself, is one of the underlying reasons why the intervention's results did not fully meet expectations. Here, it is necessary to introduce an important but easily overlooked issue, that is, "implementation fidelity issues" (Nunes et al., 2024). It refers to the extent to which those delivering the intervention are able to carry it out in line with the original plan. In other words, the closer the actual classroom implementation is to the intended design, the higher the level of fidelity. When fidelity is high, the intervention is more likely to achieve the outcomes it was expected. Studies have shown that, in some cases, interventions carried out with high fidelity can be two to three times more effective than those implemented with lower fidelity (Nunes et al., 2024).

In fact, several educational intervention projects have demonstrated that high implementation fidelity is often dependent on adequate preparation and a reasonable implementation duration. Only when an intervention is adequately supported in terms of time and rhythm does it become more likely that its effects will emerge in a stable and significant way. Taking the "Build!"

project as an example, an intervention study focused on improving students' reading and writing skills (van der Weijden et al., 2024). It has shown that after one year of implementation, the project had not yielded significant results. It was only after two years of continued intervention that a noticeable improvement in students' overall reading and writing performance became evident (van der Weijden et al., 2024). A similar pattern was observed in the school-based anti-bullying intervention proposed by Sullivan et al. (2021). The outcomes from trials in different schools, with varying intervention durations, revealed that when the intervention lasted for more than two years, the project had a remarkable impact on improving school safety. However, when the intervention period was limited to just one year, the results were far less consistent. Some schools did show a significant drop in safety problems, but others did not exhibit much change at all. Thus, the effects of short-term and long-term implementation can follow quite different trajectories.

In this project, the researcher found further support for the above conclusions through the feedback collected from teachers after the intervention had ended. A majority of participating teachers generally felt that the new model might have shown even greater effectiveness in fostering students' CT skills if the implementation period could be extended. Because both teachers and students went through a certain amount of adjustment process in the early stages of the program. Most teachers reported that the initial phase was primarily spent exploring and adapting, getting to grips with the new teaching processes and underlying principles. Likewise, students also needed some time at the beginning to understand and get accustomed to the new ways of learning, such as formulating their questions and carrying out inquiry-based tasks more independently. Meanwhile, teachers were gradually learning how to support and guide students more effectively under this new approach. This situation, in turn, highlights another important point: to ensure high implementation fidelity, both teachers and students need a reasonably generous timeframe to adapt to and gain fluency in how to teach and learn within the new model. However, in this project, the schedule fell short in that regard, as it spent too much time on teachers familiar with the new model. During the early stages of the project, the researcher engaged in multiple rounds of discussions with teachers to determine how the model should be used and what principles it followed. It was not until around a month later that most teachers began to master the model's basic operations, after which they grew increasingly confident and fluent in using it in the classroom. Therefore, one direction for improvement in future intervention studies would be to include more preparatory stages before the formal

implementation begins, especially in terms of training and supporting teachers, and in turn, training and supporting students. As the key agents of the intervention, the sooner teachers and students can feel confident and fully equipped to carry out the model, the more likely the overall fidelity of the project will be preserved (Nunes et al., 2024). Additionally, collecting more regular and targeted feedback during the early stages could also allow for quicker adjustments and responses, offering more effective support and guidance for both teachers and students, though especially for the teachers.

c) CT skills require long-term and continuous cultivation

From the perspective of how CT skills are defined, its core components in the field of education typically include several interrelated dimensions: analysis, interpretation, inference, evaluation, explanation, induction, deduction, and numeracy, among others. As a form of higher-order thinking, it is, by nature, a highly complex cognitive process (Liu & Pásztor, 2022). Consequently, according to the result in this project, the researcher believes CT skills development cannot be expected to occur overnight; instead, it requires a targeted, sustained, and supported cultivation process with patience. In the present project, although the overall improvement in students' CT did not reach statistical significance, a closer look at individual sub-indicators reveals varying degrees of positive change beginning to take shape. For instance, the increase in the analysis dimension has reached statistical significance, while indicators such as *Induction*, *Deduction*, and *Interpretation* showed promising trends that are approaching significance; no indicator showed decrease in the experimental group.

A substantial body of existing research has also demonstrated that the effective development of CT in higher education typically requires longer durations of intervention. For example, Xi and Xing (2023) reviewing 295 educational research projects conducted in Shanghai, China, highlighted one study focused on high school biology teaching that achieved its desired outcomes through a three-tiered, finally progressively structured intervention. This indirectly underscores the idea that students' skills development is a time-dependent, stage-by-stage process. Similarly, in a systematic literature review on the development of CT among university nursing students, Xiang et al. (Xiang et al., 2025) found that among interventions lasting from two to eighteen months, the most notable improvements in students' CT skills generally appeared after at least six months of consistent intervention. The findings in this project further

confirm that, the cultivation of CT skills hinges on the accumulation of sufficient time, and this is particularly relevant for younger learners.

As mentioned earlier, in this project, since both teachers and students spent nearly a month familiarising themselves with and gradually mastering the new instructional approach, this inevitably reduced the effective duration of the intervention that might otherwise have been more productive. In light of this, future implementations of the 7E IBL model as a teaching intervention framework should, wherever possible, extend the intervention period, ideally to cover at least two academic terms, or preferably a full year or more. However, it is worth noting that, despite the limited duration of the intervention, the experimental data showed a statistically significant growing in the experimental group's CT disposition. This outcome suggests that, by the end of one term, both teachers and students had, to a considerable extent, learnt how to teach and learn within the new instructional framework. While we cannot entirely rule out the possibility that the effectiveness of the intervention was still somewhat constrained by participants not having fully adjusted to the model, this influence appears to have been mitigated to a degree, thus lending greater weight to the view that the model itself had begun to produce its intended effects. On this basis, the issue of time comes to the fore once again. That is to say, compared to shifts in CT disposition, improvements in CT skills generally require a longer and more intensive process of development. In the teacher interviews, some teachers explicitly noted that, although overall changes were not yet statistically significant, they had observed noticeable leaps in CT skills among certain individual students. This observation further supports an important conclusion: that the 7E IBL model in this project had already begun to have a positive impact on students' CT skills. However, the full manifestation of that impact, its real effectiveness and potential, may only become statistically evident with longer-term accumulation and deeper engagement over time.

Meanwhile, it is imperative to stress that the “accumulation of time” mentioned here does not simply refer to the passage of calendar time. More crucially, it highlights the importance of students repeatedly practising and transferring skills, continually engaging in self-adjustment during sustained cognitive activity, and gradually building experience in applying CT to knowledge analysis (Dong, 2024). In other words, the growth of CT skills is rooted in long-term, continuous, and well-targeted practice. At the same time, time alone is not enough. To

nurture this ability effectively, appropriate teaching content and methods are equally essential. Students also need sufficient space and time to absorb, reflect on, and apply this mode of thinking within a relatively structured environment. Although the process is often slow, cultivating CT—as a form of “thinking about thinking”—is inherently a systematic process that demands both patient waiting and sustained support (Xi & Xin, 2023).

8.2.3. Underlying mechanisms and theoretical foundations of the 7E IBL model’s impact on students’ CT skills and dispositions

8.2.3.1. *Changes on CT dispositions*

Following the intervention, students in the experimental group demonstrated a statistically significant improvement in their CT dispositions, whereas those in the control group showed almost no change. Qualitative data supports this finding through teacher feedback providing evidence that students in the experimental group displayed greater learning motivation throughout the intervention. This was reflected in students’ increased initiative, more frequent and in-depth questioning, sustained interest in open-ended questions, and steady improvement in collaboration and communication skills. These positive developments were only observed among students in the experimental group, with no comparable progress evident in the control group. The results offer partial confirmation of the effectiveness of the 7E IBL teaching model, suggesting that even within the span of a single academic term, it can play a meaningful role in enhancing secondary students’ CT disposition. In the following section, the researcher will draw on theoretical frameworks and empirical data to explore in greater depth the underlying mechanisms and key contributing factors that support the development of students’ CT skills and disposition through the 7E IBL model.

8.2.3.2. *Developing a coherent knowledge base as a foundation for CT*

a) 7E IBL model: Preparation – **Elicit**

As Ribeirinha et al. (Ribeirinha et al., 2024) emphasise, a firm theoretical grounding is not merely helpful but essential for students to conduct scientific inquiry effectively and with direction, and it is a crucial prerequisite for students to engage confidently in STEAM inquiry activities. Only when students have established a coherent and well-structured knowledge system can they meaningfully transfer theoretical understanding into practical application within real-world contexts (Argote & Ingram, 2000). In line with this view, the 7E IBL model places particular emphasis on combining pre-lesson review of prior knowledge, introduction

to core concepts and skills, with post-lesson consolidation. The importance of reviewing earlier content is especially evident in contexts such as participant school, where STEAM lessons are scheduled every two weeks or even less frequently. According to teacher feedback reported in the findings chapter, students tend to forget previous content easily under such intervals, which poses a challenge given that each session typically builds on the last. According to teachers' interviews, students in the control group asked more frequent and fundamental questions related to prior subject knowledge or software functions, which disrupted the classroom pace. As a result, the discontinuity hinders the flow and depth of inquiry-based activities. As such, in settings where lessons are spaced further apart, helping students revisit prior learning systematically becomes a vital step in ensuring the coherence and progress of inquiry-based learning.

b) 7E IBL model: Preparation – Concept and skill introduction

Secondarily, regarding “concept and skill introduction”, the second step of the Preparation phase in the 7E IBL model (new knowledge input), which refers to the teacher’s purposeful introduction of key concepts and necessary technical skills before students begin their inquiry activities. The key rationale for this approach stems from findings in previous research, which suggest that it is extremely challenging for students to undertake complex, open-ended inquiry tasks effectively when they lack an understanding of the underlying classroom knowledge, such as fundamental concepts or disciplinary principles (Bónus & Antal, 2021). This is particularly true for beginners: in the absence of teacher guidance, fully open inquiry can easily become directionless and unproductive, leaving students with little to no meaningful learning and, in more serious cases, such unguided exploration can amount to little more than wasted time (Clark et al., 2012). Therefore, if teachers aim to implement the 7E IBL model effectively in classroom inquiry activities, it is important that they first build in some essential preparatory steps, particularly ones that introduce key concepts and foundational skills that students will need, such as how to use relevant software. This kind of groundwork does not just help students feel more equipped; it also enables them, in the design phase, to select meaningful topics from real-world scenarios and develop plans with clear learning objectives. With that in place, they are in a much better position to engage in the inquiry process using their CT skills, observing, interpreting, and justifying their findings with logical reasoning. And in fact, problem-solving through inquiry is not only a way to apply what one has learnt, but it is also one of the most powerful ways to extend and reinforce that knowledge (Wilson, 2020). When done in a hands-

on and engaging way, such inquiry-based tasks can have the added benefit of positively supporting students' CT dispositions by giving them space and reason to think more deeply, reflect more critically, and stay curious.

c) 7E IBL model: Extension – Subject matters summary and extension

Finally, from the perspective of cognitive science, knowledge consolidation is regarded as a fundamental component of human learning, serving as the mechanism through which context-dependent and relatively fragile knowledge—often acquired during exploratory activities—is reinforced following its initial encoding (Morales-Martinez et al., 2021). This is achieved through both replay and deliberate, conscious efforts to strengthen and stabilise what has been learned, gradually integrating it into the long-term memory network (Zhou et al., 2024). The importance of this process cannot be overstated, as it largely decides whether disciplinary knowledge can be retained over time and whether it can be accessed and applied effectively when needed. With appropriate strategies, however, students are better positioned to retain what they have learned and apply it effectively, taking greater ownership of their learning outcomes (Rodriguez, 2015). The same principle applies when it comes to fostering essential learner capacities and productive academic habits, developing these aspects in a meaningful and sustainable way typically requires consistent stimulation, as well as repeated opportunities for knowledge to be consolidated and reinforced over time (Abrami et al., 2015). Take CT skills and dispositions, for example; neither emerge overnight. Instead, they are cultivated gradually as part of an ongoing process involving both the development of cognitive habits and the shaping of particular ways of thinking. CT dispositions, in particular, are best understood not simply as abilities but as tendencies; they are habits of mind and attitudes towards thinking that reflect a person's willingness to engage critically (Facione, 1990). For such dispositions to take root, students need repeated engagement in inquiry, accompanied by systematic opportunities for reflection and review. With sustained encouragement and deliberate guidance, these habits can eventually become internalised, embedding themselves within students' everyday learning routines. Over time, they may evolve into enduring traits of character rather than remaining isolated performances within the classroom setting (Facione, 1990).

According to the data analysis results of this study, students demonstrated a general improvement in both CT skills and dispositions, with the most pronounced progress observed

in CT dispositions. This shift, to some extent, confirms the positive role played by the 7E IBL model, including in the **Extension** section where teachers not only provided a systematic summary of the key content covered in the lesson but also designed near-transfer tasks (please refer to section 8.2.3.3. Fostering CT through repeated application in knowledge transfer tasks) that guided students to apply what they had learned to new contexts, thereby contributing to both the internalisation of disciplinary knowledge and the development of CT. Based on teacher interview feedback presented in the Findings chapter, many teachers noted that during the final phase of the lesson—when key knowledge was being summarised—students’ attention became markedly focused, with nearly all eyes and thoughts returning to the teacher. In contrast, students in the control group tended to appear increasingly disengaged as the lesson drew to a close. This suggests that the final phase of the 7E IBL model not only effectively sustained students’ attention but also offered a valuable opportunity to cultivate positive learning habits. At the same time, it served as a final review and consolidation of knowledge, thereby further enhancing learners’ overall knowledge system. Hence, it was precisely this element of the lesson design that allowed the subject knowledge initially constructed through inquiry to be further processed and deepened. As students activated information stored in their short-term memory, they were able to revisit what they had previously learned and, through this process of “reviewing the old to understand the new”, not only recall and integrate their earlier knowledge structures but also reinforce their CT skills and dispositions. This process then supported the reactivation and retrieval of prior knowledge, and it allowed students—through repeated engagement and reorganisation—to supplement, adjust, and reconstruct relevant knowledge and thinking strategies, thereby enhancing the coherence and complexity of their cognitive frameworks and further developing the depth and flexibility of their CT (Morales-Martinez et al., 2021).

In conclusion, working over time to help students gradually construct a coherent knowledge system through *‘reviewing prior knowledge, introducing concepts and skills, summarising subject matter, and extending knowledge’* is one of the cornerstones and reasons why the 7E IBL model is such an effective way to increase students' CT. It does so by revisiting prior knowledge before class, introducing new concepts and essential skills in a connected and meaningful way during lessons, and then expanding and reinforcing that knowledge systematically after class. This ongoing process plays a key role in helping students build a more coherent and solid knowledge base bit by bit. What is particularly important is that it not

only allows students to get into the learning mindset more quickly during lessons but also lays the groundwork for the smooth progression of STEAM courses and, crucially, for achieving deeper inquiry. After all, only when students are able to retrieve and piece together what they have learnt before can their explorations be meaningfully extended and deepened, leading them step by step towards real problem-solving and the development of scientific thinking. At the same time, the efficient and structured nature of the inquiry process helps students grow in other ways as well: they become more curious about the subject, more interested and invested in learning, and more confident in their own abilities. They also begin to approach learning with a more open and inquisitive mindset—actively seeking evidence, asking questions, and seeking to uncover the truth. Through this, their thinking becomes more mature and reflective over time. Moreover, these are not just nice ideas in theory—the experimental data in this project supports this. Students in the experimental group demonstrated clear and statistically significant improvements in various metrics of CT dispositions. This provides strong support for the idea that the 7E IBL model, by establishing these closed loops of knowledge, effectively plays a role in fostering students' CT dispositions across multiple dimensions

8.2.3.3. Deepening thinking through interaction

a) The Constructivist perspective on the positive impact of multi-dimensional interaction in knowledge acquisition and higher-order thinking development

According to Vygotsky's constructivist theory, learners entering adolescence (approximately from the age of eleven onwards) begin to develop the capacity for logical reasoning and abstract thinking that transcends direct experience, while their cognitive structures also become increasingly complex (Vygotskiĭ et al., 1978). At the same time, this developmental stage marks a critical period during which cognition and emotion evolve in tandem, and students' metacognitive abilities—that is, their capacity to monitor, regulate and reflect upon their own cognitive processes—become progressively more sophisticated (Flavell, 1971). They gradually develop relativistic thinking, becoming aware that truth is not always absolute but often contingent upon context and shaped by cultural backgrounds. This shift leads them to question authoritative knowledge, sometimes manifesting in attitudes that appear rebellious or resistant (Perry & Knefelkamp, 1999). Nevertheless, it is precisely this state of scepticism that provides fertile ground for the emergence of a critical and inquiry-oriented mindset. Drawing on these developmental characteristics, the 7E IBL model deliberately incorporates dialogic interactive teaching strategies to foster students' growth in CT.

Vygotsky's constructivism emphasises that knowledge is not acquired in isolation but rather co-constructed through social interaction within a community (Vygotskiĭ et al., 1978). In classrooms guided by the 7E IBL model, this principle is enacted in tangible ways. For example, peer instruction—a practice rooted in constructivist theory—encourages student collaboration in pairs or small groups, where learning is driven by dialogue and shared problem-solving (Mazur, 1997). By interactions with peers and teachers, students sharing their experiences, discussing ideas, and exploring diverse perspectives, which can form more nuanced and multidimensional understandings of concepts. Research has shown that peer instruction can significantly enhance students' conceptual understanding and problem-solving abilities (Crouch & Mazur, 2001; Deslauriers et al., 2011). However, the benefits of peer interaction also have limitations. For example, as discussions often lack the depth or direction necessary for deeper inquiry, students are confronted with more abstract or complex issues; thus, the unguided collaborative learning may fail. Vygotsky's theory identifies a crucial learning area, the Zone of Proximal Development (ZPD) which introduce the difference between a student's unassisted capabilities and their potential accomplishments when guided by a more knowledgeable person. Essentially, the ZPD is the fertile ground where guided interaction fosters the most significant cognitive growth (Vygotskiĭ et al., 1978). Since learners within the ZPD have not yet fully developed the capacities for independent problem-solving, the transformation of potential into actual competence often relies on scaffolding from others—whether through expert guidance or peer interaction—which helps internalise new knowledge and skills (Vygotskiĭ et al., 1978).

This notion of scaffolded learning is concretely embedded in the 7E IBL model, for example during the 'Elaborate' phase of inquiry. At this stage, students are encouraged to extend and deepen their discussions through mini tasks that prompt them to build upon prior exchanges, explore alternative perspectives, and refine their thinking. For instance, when a student presents a particular claim in a group discussion, peers may respond with critical questions, creating an opportunity for the teacher to intervene strategically—often through Socratic questioning—to help the group examine the assumptions and logical coherence behind the argument. In such moments, when differing viewpoints appear, it reflects dialogue, allowing the dynamic process of collaborative meaning-making to happen. Through this iterative exchange, which includes challenge, clarification, and reconsideration, students gradually internalise these external interactions, turning them into cognitive tools that enhance their capacity for CT.

b). Socratic questioning from teachers as a driving force in dialogic interaction

Socratic dialogue invites students to question and probe more deeply, encouraging the awakening of a critical disposition, while peer instruction and other forms of group-based collaborative learning enhance their capacity for abstract reasoning and logical thought through sustained discussion and the exchange of diverse viewpoints—thus creating a favourable context for the cultivation of higher-order thinking. If constructivism can be seen as the fertile soil of interactive learning, then Socratic questioning serves as the act of sowing the seeds. Socratic questioning refers to a pedagogical technique in which teachers pose a series of systematic, well-structured, and probing questions to guide students in examining the assumptions underlying their conceptual judgments and further analysing the reasons behind them (Delić & Bećirović, 2016). Such questioning typically begins with open-ended prompts and, in the context of STEAM education, is often centred around the core inquiry themes of the lesson. Rather than judging students' answers right or wrong, teachers should encourage students to think independently, explore ideas in depth, and articulate their perspectives with clarity step by step (Barnes & Payette, 2017). As a result, the dialogic, inquiry-based approach helps students become aware of what they master and what they do not understand, and it cultivates their cognitive abilities through sustained reflection and discussion (Yang et al., 2005). Typical forms of Socratic questions include in Table 52:

Socratic Question Type	Question Example
Questions for clarification	Could you elaborate further on what you mean by '...'? Could you give me an example? Could you illustrate what you mean?
Questions that probe depth and assumptions	What are we assuming here? What are some of the difficulties we need to deal with? What factors make this a difficult problem?
Questions that probe precision	Could you be more specific? Could you give me more details? Could you be more exact?
Questions that probe relevance?	How does that relate to the problem? How does that bear on the questions? How does that help us with the issue?
Questions that probe reasons and evidence	What evidence do we have to support that claim? How could we verify or test that? How could we find out if that is true?
Questions about viewpoints or perspectives	Is there an alternative way to look at this issue? Do we need to look at this from another perspective? Do we need to consider another point of view? How can we look at this in other ways?
Questions about implications and consequences	What would be the consequences if we were to adopt this position?
Questions about the question	Why is this question important? Is this the most important problem to consider?

Table 52: Different types of Socratic Questions and their examples (Paul & Elder, 2007).

Another key advantage of Socratic, dialogue-based instruction lies in its ability to make the learner's thinking process visible (Collins & Stevens, 1983). This not only enables students to become more clearly aware of their own cognitive pathways, but also allows others to 'see' how their thinking unfolds. When teachers pose questions listed in above tables, students' thinking is immediately activated, prompting them to enter a state of metacognitive reflection. As noted in the Findings chapter of this project, these questions were initially posed externally by the teacher; however, as group-based collaborative learning progressed, students began initiating questions among themselves, particularly during the presentation stage, where "why" and "how" questions frequently emerged during Q&A sessions. Over time, students gradually

internalised these externally modelled questioning strategies and began to engage in self-directed inquiry within the learning process, for instance, asking themselves, “What evidence supports my argument?” Our analysis of the qualitative data also revealed that the number of questions posed by students in the experimental group increased significantly, with a growing proportion focused on “why” questions, those that aim at deeper cognitive exploration and knowledge extension. This phenomenon further supports the argument that the 7E IBL model plays an active role in fostering students’ CT, through its emphasis on diverse and sustained interaction.

In conclusion, in this project, multifaceted dialogic interaction constitutes one of the core elements in the design of the 7E IBL model and is embedded across several of its key stages, and it is also a key mechanism in supporting the development of students’ CT. For instance, the small-group inquiry activities encouraged students not only to pose questions actively throughout the learning process, but also to engage in spontaneous exchanges with the teacher, facilitated by an environment that supported open communication at any time. At the same time, the model fostered sustained peer discussion within groups, incorporated interactive questioning during the post-inquiry presentation phase, and, finally, embedded collaborative inquiry tasks in the extension phase—all of which illustrate the model’s strong emphasis on interaction as an integral part of the learning experience. This multi-layered and multimodal approach to interaction is grounded in constructivist theories, represented by Vygotsky, theories of peer instruction, the ZPD concept. At the same time, it draws inspiration from collaborative problem-solving as observed in classroom practice, integrating teacher-led Socratic questioning with dialogic teaching and other highly interactive pedagogical strategies. The aim is to stimulate students’ intellectual engagement and sense of participation through authentic and sustained communicative processes so that, through continuous articulation and reflection, they may gradually develop understandings that are not only more complex and nuanced but also critically informed. As a result, this interactive model not only enhances students’ comprehension and integration of knowledge but also subtly cultivates their CT skills and gradually fosters the dispositions necessary for CT, thereby laying a solid foundation for the development of higher-order thinking.

8.2.3.4. *Fostering CT through repeated application in knowledge transfer tasks*

Near transfer refers to students' ability to apply acquired knowledge in similar contexts and transform it into practical, actionable skills, where usually new and old tasks often share the same technical platform and operating framework (Perkins & Salomon, 1992). For example, after learning how to use a 3D printer to create a toy car, a typical near-transfer question might be: "What else can you make with the 3D printer?"—such as printing a small household furniture like a phone holder. In contrast, far transfer refers to the application of acquired skills in entirely different contexts, where the process often requires additional technical support from other disciplines (Barnett & Ceci, 2002). For example, students may draw on the thinking model of prototype iteration and rapid trial-and-error, which they have developed through 3D printing tasks, and apply it to the development process of a new software product. This type of transfer goes well beyond the original learning context, as it demands the integration of knowledge and methods from multiple domains. Given this distinction, it is important to note that the extension phase of the 7E IBL model, as implemented in this project, is essentially designed to consolidate and extend the core knowledge of the lesson and has to be finished in class, considering the cost of time. As such, the questions posed in this phase are more often aligned with near transfer. With this clarification in mind, we now turn to a more in-depth discussion of how the extension phase contributes to students' acquisition of subject knowledge and the development of CT.

More specifically, near-transfer tasks within the 7E IBL model appeared primarily in two stages: the Elaborate phase of the inquiry stage and the final extension phase of the lesson. While both involve near-transfer tasks, their modes of implementation and pedagogical aims differ slightly. The elaborate phase typically centres on a specific disciplinary concept, with the teacher posing a near-transfer question and guiding students through a response or hands-on task. In contrast, the extension phase takes place at the conclusion of the lesson and requires students to actively synthesise and transfer all the knowledge covered in the session to a similar but slightly modified context, posing new questions, developing plans, and engaging in group discussion. For example, after students have learned how to use laser cutting software to create circular designs, a task in the elaborate phase might ask: "Can you draw a square or another shape?", followed by immediate practice. By comparison, the extension task is more open-ended: students are encouraged to consider "What else could we create using laser cutting?" and collaboratively design a feasible project plan based on the techniques they have just learned. According to teacher interview data, this dual-layered design supports learning in two key ways:

it helps students consolidate their newly acquired skills into a more stable and actionable knowledge structure, and it significantly enhances classroom engagement and enjoyment by adding a layer of purposeful creativity and autonomy.

The essence of knowledge extension is the integration, transformation, and connection of prior knowledge (Beker, 2008). It transcends the mere accumulation and surface-level comprehension of information, laying the foundation for decontextualisation, which is a process through which knowledge evolves into internalised understanding that can be flexibly applied across various contexts (Beker, 2008). During near-transfer tasks, students take a critical step in transforming knowledge into applied competence. In the interdisciplinary STEAM education, such tasks offer an ideal platform for cultivating CT. In particular, the extension phase of the new 7E IBL model in this project introduces well-structured, moderately complex, and manageable transfer tasks that not only deepen students' application of knowledge but also stimulate their cognitive potential. Within these tasks, students cannot rely on rote recall; instead, they must engage in analysis, evaluation, and reasoning that shifting the focus of thinking from "what is the answer" to "how" and "why". The extension phase often triggers students' metacognitive activity, which is to think about their own thinking. Students pause to reflect on which aspects of their existing knowledge are relevant to the task at hand, revisit problems encountered during the inquiry phase and examine the similarities and differences. Metacognition involves planning, monitoring, and regulating one's cognitive processes (Schraw & Dennison, 1994). In contrast, simple recall-based questions (e.g. "What is the density of water?") rarely provoke such high-level thinking. Near-transfer tasks, however, demand students to engage in planning, monitoring, and self-evaluation, the core components of metacognition.

Metacognitive Prompt	Critical Thinking Prompt	Critical Thinking Response
What do I know from the toy car activities that can help me produce the phone holder?	What's the difference between a toy car and a phone holder?	Toy car: realistic appearance and fun. Phone holder: must bear weight, be stable and durable.
Based on prior experience what is the first step to start this?	Compared to a toy car, what material should I use for a phone holder?	Analysed the characteristics of various materials. PLA is brittle and does not support much weight, causing the holder to break. PETG is tougher and often used for functional parts. ABS has the highest strength and is less prone to breaking, but it tends to warp and is harder to print. Based on this comparison, PETG was selected for the phone holder.
How can I make the phone holder stronger?	What design changes can improve the structural strength of the holder?	Based on mechanical principles, the overall structural strength can be improved by increasing infill density and wall thickness. Therefore, I increased the infill from 15% to 30% and added three wall layers.
If the print fails during actual operation, why? What can I do?	What are the possible causes of print failure, and how can I prevent them?	Analysed possible reasons for failure. For instance, a large base area may lead to uneven cooling and warping. Three solutions considered: 1) Increase the bed temperature. 2) Add a brim in the slicer to enhance adhesion. 3) Use a heated enclosure. Considering cost, time and convenience, the second option was selected.

Table 53: Examples of Metacognitive and CT Prompts, and Corresponding CT Processes in STEAM Activities

While metacognition addresses how we think, CT concerns how to think better, in this sense, metacognition serves as the key “switch” that activates CT (Diane F. Halpern, 2014). At its core, CT is the skilful analysis and evaluation of information to facilitate rational decision-making (Scriven & Paul, 1987). If metacognition is understood as the system responsible for generating questions, then CT functions as the system for analysing and responding to those

questions (Diane F. Halpern, 2014; Kuhn, 1999). For example, as showed in Table 53, in the near-transfer task mentioned earlier—using a 3D printer to create a small piece of furniture, such as a phone holder—students are first prompted to ask metacognitive questions (“What do I know from the toy ... or “How can I make the structure more stable?”), and then engage in CT processes to evaluate options, make decisions, and justify their choices.

Overall, learners demonstrating higher levels of CT are typically more engaged in metacognitive processes, especially in the metrics of strategic planning, evaluative judgment, and reflective adjustment (Ku & Ho, 2010). During complex near-transfer tasks in the 7E IBL model, when students encounter confusion or disagreement during group discussions, their metacognition is activated, alerting them that existing automatic strategies are insufficient and prompting them to draw upon CT skills. The same applies to inquiry-based learning process, where students are frequently challenged to question, reflect, and refine their ideas. This process initiates the development of CT, prompting actions such as analysis, questioning, evaluation, rejection, and adaptation, through which students probe and assess the ideas and ideologies they encounter. Thus, every near-transfer task becomes a dynamic cycle of “Metacognitive activation - CT engagement – Reflection and feedback”. These cycles not only enable students to solve concrete problems but also serve as repeated exercises in core intellectual practices such as reasoning, evaluating, and analysing. Over time, with repeated exposure to inquiry activities and extension-phase near-transfer tasks in every 7E IBL-based STEAM lesson, students’ capacity to engage in CT will become increasingly refined, and even begin to operate with a degree of automaticity.

8.3. Other factors impacting students’ CT in STEAM education

8.3.1. Feedback from participants teachers on the 7E IBL model

During a pilot teaching activity, especially in the context of STEAM education, it is important for researchers to pay attention to the role of teachers' feedback, as it often becomes a key factor in improving the overall teaching efficiency when designing an instructional teaching model in real classroom settings (Grancharova, 2024b). While students' experiences are certainly valuable, teachers are often the only other direct participants who can observe, respond to, and influence how subject knowledge is delivered and received during the lesson (Margot & Kettler,

2019). In integrated and hands-on STEAM classrooms, their observations reflect what is happening on the surface and some of the deeper challenges in translating theoretical ideas into workable classroom practice (Grancharova, 2024a). At the same time, researchers also need to understand that the way teachers experience about the model, whether they find it helpful, practical, or even just manageable that can significantly influence whether or not the implementation is ultimately successful (Papagiannopoulou & Vaiopoulou, 2024). For this reason, teacher feedback often serves as a first-hand, practical reference point that helps designers understand what the model looks like from the ground level, and what kinds of things might need to be adjusted. In next sections, the researcher will examine the relationship between teachers' user experience and actual teaching practice from three different angles: the overall structure of the 7E IBL model, how the process works in real classroom conditions, and the extent to which the model is adaptable to different teaching situations.

Regarding the structure of the 7E IBL model, all the participating teachers expressed a generally positive attitude, noting that the model included all the essential elements that a sound instructional framework should have. Many of them even described it as quite comprehensive, or even “perfect” in its design. However, this completeness turned out to be a double-edged sword when it came to actual classroom application. On the one hand, because they saw value in every component of the model, they felt reluctant to skip or leave out any part of it. On the other hand, because the model included so many stages it became difficult, if not impossible, to fit everything into a single lesson, especially under the constraints of limited teaching time. Time management, therefore, became a significant challenge in trying to implement the full model. Many scholars in the field of education have pointed out that there is no such thing as 'one size fits all' teaching model that can be applied universally across different classroom scenarios (Loeser, 2013). As Jr and Konopasky (2018) argued, there is no single educational model that can fully accommodate all teachers' diverse learning goals and needs. A theory that works well in one context may become entirely unsuitable in another, and teachers often find themselves adapting or even abandoning a theory when faced with a different classroom situation. This view is also indirectly supported by Resnick et al. (2019), who reviewed a range of studies and practical experiences in the field of Dialogic Education in the 21st century. They concluded that no single teaching model consistently proves effective across all educational settings or learning environments, further highlighting the need for flexibility and context-specific adaptation in teaching practice.

Thus, rather than aiming to identify or construct a so-called perfect teaching model, this project places its primary focus on fostering students' CT skills, while also taking into account other important dimensions such as student engagement, mastery of subject knowledge, and the overall usability of the model from the teachers' perspective. The intention is not to abandon the pursuit of a sound or professionally designed instructional model altogether, but rather to ensure that, based on a broadly well-structured and pedagogically grounded framework, the emphasis is placed more explicitly on cultivating students' ability to think critically and independently. For instance, in this context, traditional measures of academic performance, such as test scores, have been intentionally moved down the list of priorities. This is because STEM education, as framed in this project, emphasises a more hands-on and exploratory approach to learning, aiming to guide students toward discovering the underlying principles of knowledge through practice, rather than simply preparing them to achieve high marks on standardised assessments.

Increasing the model's flexibility was also a recurring theme in participating teachers' feedback, especially in light of the varied demands of real classroom teaching. When it comes to pedagogical models, flexibility plays a vital role. As Darling-Hammond (2017) pointed out, having space for adjustment is essential in preparing for diverse classroom scenarios and addressing students' varied backgrounds, emotional needs, and the social environments in which they grow up. Although the teachers considered the initial version of the 7E IBL model somewhat rigid, this issue was gradually addressed through a process of co-refinement. The researcher worked closely with the participants to adjust the model and improve its user-friendliness. During this stage, feedback from the teachers, who had firsthand experience with the model in practice, proved invaluable. In parallel, relevant literature was also consulted to explore how other educational model designers have approached the challenge of improving flexibility. Therefore, when designing the 7E IBL model, the researcher deliberately retained certain stages such as *Elicit* (which focuses on reviewing students' prior knowledge) and *Elaborate* (where near-transfer questions are used) to check whether students have actually mastered the concepts explored during the inquiry activities. As a result of this collaborative process, the revised model was better aligned with real teaching needs and more responsive to teachers' expectations in terms of structure, clarity, and adaptability.

In general, the 7E IBL model received positive feedback from the participating teachers. It was designed with the aim of offering STEAM educators a clear and systematic framework to guide the lesson planning process, outlining each stage of STEAM teaching step by step. According to the teachers, while the model does present a certain level of complexity, its overall difficulty remains manageable. They appreciated the degree of freedom it allowed in terms of content selection and adaptation, which gave them room to adjust each lesson to suit their own teaching context. In particular, teachers provided valuable suggestions regarding the model's structure, flow, and practicality. They recognised its strengths in offering a logically organised and content-rich framework, but also pointed out the need to highlight the core focus of the model more clearly (CT is the core focus in this project), so that users can more intuitively grasp its key points during lesson planning. Increasing the model's flexibility was also a recurring theme in their feedback, especially in light of the varied demands of real classroom teaching.

8.3.2. Teachers' enactment as a key role: their professional development and support

Literature has identified two core challenges in teacher-led instructional interventions: first, ensuring that teachers possess an accurate and in-depth understanding of the instructional goal, in this case, CT; and second, translating this understanding into sustainable and effective classroom practice (Guskey, 2002; Roehrig & Kruse, 2005). This project addressed these two closely interconnected challenges through a multi-dimensional professional development framework, aiming to support teachers in shifting from passive implementers to reflective, proactive practitioners.

8.3.2.1. Teachers' conceptions of CT: Perceptions of CT's value and educational significance

To lay a solid foundation, the project first aimed to establish a clear and shared understanding of CT. Although the concept of CT is defined and understood differently across disciplines, most notably from philosophical, psychological, and educational perspectives, this project focuses primarily on its application within educational practice. Accordingly, the adopted definition aligns with Bloom's taxonomy of higher-order thinking skills (analysis, synthesis, and evaluation) viewing CT as a goal-directed cognitive ability to analyse, categorise, and systematically process information, evidence, and arguments in order to form sound judgments

and make reasoned decisions or solve complex problems, plus the CT dispositions to use this skills (Choy & Cheah, 2009). With this conceptual foundation in place, the following section will explore how teachers' own understanding and perceptions of CT influence the development of students' CT.

In this project, participant teachers, being the primary agents in the delivery of CT instruction, play a central role in the effectiveness of implementation. According to Shulman (1986) and Guskey (2002), teachers' understanding of subject matter and pedagogy, along with their professional beliefs, are foundational to meaningful instructional change. Their conceptualisation of CT, practical competence, and access to appropriate instructional resources form the basis for successful teaching. If the instructional intervention is considered an external factor, then the teacher, as the principal agent operating the 7E IBL model, serves as the internal factor determining its success, particularly through their grasp of both the model itself and the underlying concept of CT. In this study, the quality and depth of the intervention were shaped directly by how teachers understood CT, what they believed about its value, and how they perceived their instructional roles (Guskey, 2002). When a mismatch exists between a teacher's personal conception of CT and the intended learning goals of the intervention, its effectiveness is likely to be undermined (Roehrig & Kruse, 2005). Prior research has shown that when teachers hold vague, incomplete, or inaccurate understandings of CT, for instance, equating it with rote memorisation, it becomes challenging to develop students' CT in meaningful ways (Choy & Cheah, 2009). In many educational settings, the cognitive level of their teachers shapes the cognitive ceiling for students' CT development (Choy & Cheah, 2009).

Thus, to ensure that teachers' understanding extended beyond the theoretical level, the intervention integrated several key strategies. For example, the researcher conducted multiple rounds of one-on-one training with each teacher, repeatedly clarifying the educational definition of CT and checking their understanding of this concept. Second, to directly address the potential misconceptions teachers may have about CT concepts, the researcher employed a curriculum co-design method. This method not only helped teachers deepen their practical experience with the 7E IBL model, but also modelled how to implement it and required them to articulate their own understanding of CT in context, thereby enhancing their sense of professional agency and the relevance of their teaching. In the meantime, this allowed

researchers to identify and correct their potential misunderstandings of CT concepts in real teaching design situations, thereby closely integrating theoretical cognition with teaching practice. This is explained in detail in the teacher enactment section below.

8.3.2.2. Teacher enactment of CT instruction:

Once a shared understanding of the concept had been established, the core challenge of the project lay in ensuring that the intervention could be implemented consistently and effectively within real classroom settings (Furtak et al., 2012). This process, requires multidimensional support to gradually build teachers’ trust in the adopted teaching model, improve their operational fluency, and establish a systematic professional development mechanism that can continuously enhance the capacity to teach CT (Darling-Hammond et al., 2017; Guskey, 2002). Guided by the literature, the project implemented a multi-dimensional support system, see Table 54, designed to empower teachers in their role as intervention implementers.

1.	<i>Establish a sustained and structured support system</i> Before implementation, researcher provided each teacher with one-on-one training. During the first month, the researcher conducted post-lesson interviews and discussions after every session, with on-demand support available throughout the period.
2.	<i>Embed CT into the context of subject - STEAM education</i> By leveraging the hands-on, interdisciplinary nature of STEAM classrooms, the project encouraged students to think critically, question assumptions, and grow through engagement with complex and authentic tasks.
3.	<i>Encourage teachers to engage in active learning and participation</i> Co-designing each lesson with researchers (co-working) enabled teachers to gain a deeper understanding and hands-on experience with the 7E IBL model, thereby enhancing instructional relevance and fostering a stronger sense of professional autonomy.
4.	<i>Create teachers learning communities or groups</i> Teachers were encouraged to form collaborative support groups, providing a sustainable platform for peer dialogue and mutual growth through collective inquiry and practice.
5.	<i>Mechanism for feedback and reflection</i> Researchers regularly collected teacher feedback during implementation and worked collaboratively with them to analyse the difficulties and challenges emerging from classroom practice, continuously refining the intervention strategies to enhance their practicality and impact.
6.	<i>Support from school leaders</i> The explicit commitment and encouragement of the principal of the participating school created favourable conditions for the advancement of the intervention. His recognition of STEAM education and active support for teacher participation laid an important foundation for the success of the project.

Table 54: A multi-dimensional teachers professional development support system (Desimone, 2009; Garet et al., 2001)

As showed in above Table 54, the intervention was embedded within the context of STEAM education, which emphasises hands-on learning and interdisciplinary integration, an environment well-suited to engaging both teachers and students in critical questioning and sustained CT processes. To foster an environment of continuous improvement, teachers are encouraged to form peer support groups, creating a sustainable platform for professional dialogue and collective growth. Complementing this peer-based model, a structured system of feedback and reflection was also established: researchers regularly gathered teacher feedback and collaborated with them to analyse challenges and refine strategies. Finally, the success of the intervention was underpinned by full support from the school principal, whose clear commitment to STEAM education provided essential institutional backing for its effective implementation.

8.3.3. The role of learning journals and metacognitive reflection in cultivating CT

8.3.3.1. The role of the notebook as a learning journal:

The content of the notebook was designed by the participating teachers and consisted of two main components: the first was a summary of subject knowledge provided by the teacher, and the second included near-transfer mini tasks. The notebook was distributed to students in printed form and was intended for use during each class session, where students would complete the assigned tasks. At the end of the term, teachers reviewed the notebooks and provided either a grade or written feedback. Multiple pedagogical considerations informed the design of the Notebook. One of its core functions is to support students in systematically consolidating key disciplinary knowledge from each lesson, with teachers summarising and recording the main content at the end of each session. This effectively transforms the Notebook into a form of learning journal within the STEAM education context. Given that project-based learning lacks a fixed or structured curriculum, the Notebook addresses the absence of a conventional textbook by providing students with a visible, organised record of their learning, one that can be reviewed after class and previewed beforehand, thereby facilitating the gradual construction of a coherent and robust knowledge base (Marzano, 2004). According to the previous research, structured knowledge recording noticeably enhances secondary students' learning, particularly in terms of information integration, conceptual transfer, and long-term memory formation (Stanley & Lewandowski, 2016).

However, based on both the literature review and classroom observations in this project, we identified potential for further improvement in the guided notebook design. Specifically, to increase students' engagement in the process of knowledge construction, we shifted from a teacher-led summarisation model to a more participatory approach. This involved presenting key content in a guided "fill-in-the-blank" format, allowing students to actively complete and internalise core concepts during the learning process (Fiorella & Mayer, 2016; Konrad et al., 2009). This format not only fosters deeper processing of key content but also strengthens students' task awareness and learning motivation (Fiorella & Mayer, 2016). Roediger and Karpicke (2006a) highlight that, compared to rote repetition, moderate fill-in-the-blank designs promote deeper cognitive engagement with disciplinary knowledge. Such formats facilitate long-term retention and enhance knowledge transfer, as the act of recalling and matching information requires students to access and reorganise their prior knowledge actively. In doing so, learners engage in meaningful cognitive processing and knowledge construction, which lays a strong foundation for subsequent extension and application tasks (Roediger III & Karpicke, 2006a).

8.3.3.2. Metacognitive and knowledge extension: cultivating CT

The second core function of the Notebook is to serve as a platform for recording and reflecting on near-transfer tasks embedded in the inquiry phase. During the Elaborate and Extend stages of the 7E IBL model, carefully designed near-transfer tasks are pre-written into the Notebook, with ample space provided for students to engage in written reflection. This design aims to prompt metacognitive reflection and foster critical transfer. Specifically, teachers guide students to draw on newly acquired disciplinary knowledge to construct a novel yet structurally analogous real-world context, within which they independently formulate an open-ended, inquiry-driven question. Students then work in groups to discuss the question and collaboratively develop a complete solution, which is documented in detail in their Notebook. Through this process, students not only reorganise and apply knowledge in authentic or quasi-authentic contexts, but also continually activate their metacognitive mechanisms through ongoing articulation, questioning, and peer feedback (Desimone, 2009). In this phase, the Notebook serves not only as a record of task execution but also as a dynamic interface where cognitive processing, knowledge transfer, and reflective learning intersect.

If the consolidation of knowledge and teacher-guided inquiry are two key components of the 7E IBL model, then the Notebook serves as a vital bridge that organically connects these core elements (Keys et al., 1999). Its value lies not merely in functioning as a record-keeping tool for disciplinary knowledge, but more importantly, in creating a cognitively and metacognitively rich "learning workspace" (McDermott & Hand, 2013). The design of the Notebook aims to help students form a complete learning loop within the new instructional model, enabling each phase of learning to interact and reinforce the others. In practice, the Notebook offers a clearly structured and highly operable paper-based platform through which students can track, document, and reflect on their own learning processes (Keys et al., 1999). It supports the organisation and internalisation of subject content while also playing an important role in fostering the development of CT. As a formative tool, the Notebook not only captures the trajectory of individual students' cognitive growth but also provides a visual record of their evolving thought processes, allowing teachers to offer more targeted and responsive guidance (Furtak & Ruiz-Primo, 2008).

According to the findings from data analysis, the "extension" phase of the learning notebook serves not only as a platform for near-transfer applications, but more importantly, as one of the concrete and assessable spaces for practising and developing CT. During this phase, students are required to formulate their own inquiry plans in response to teacher-designed tasks, a process that, in essence, activates the three types of metacognitive knowledge outlined by Flavell (1979): person variables (like, "What do I already know?" "What am I uncertain about?"), task variables (like, "What is being asked of me?" "Where are the conceptual challenges?"), and strategy variables (like, "How should I begin?" "Which plan is more effective?" "Is my approach feasible?"). As one teacher noted, students often use their notebooks to reflect on questions such as "What are the characteristics of this design?" and "What aspects need improvement?", illustrating that they are beginning to engage in strategy-level reflection. The process of planning and writing down these thoughts does not simply externalise a previously internal process but enables students to engage in self-regulated learning through planning, monitoring, and evaluating their cognitive activities (Bereiter & Scardamalia, 2013). From Schön's (2017) perspective, this aligns with what he terms "reflection-on-action", in which learners revisit their cognitive steps, examine initial assumptions, analyse the strengths and weaknesses of their ideas, and propose improvements: a transformation from passive executors of tasks to researchers of their own thinking.

Although some students' entries may appear simple, one teacher observed that they had "started to think about the pros and cons behind each design", which, for secondary school students, marks "a good beginning" in developing evaluative judgement. Despite the varying quality of entries, all participating teachers acknowledged the significant value of the notebook. One noted that students "now have a place to visualise and track their thinking" rather than relying solely on their internal thoughts, while another suggested that notebook completion would likely improve if its importance were clearly explained at the beginning of the term or linked to final subject grades. Moreover, teachers reported that students were "recording their ideas throughout the entire semester" and that a routine of writing reflections in every session allowed them to "gain clearer awareness of where they are in their learning". The notebook, therefore, acts not as a passive repository but as an active and integrative cognitive workspace where the processes of knowledge consolidation, problem-solving, and metacognitive regulation are continuously interwoven (Sampson et al., 2011). By encouraging students to articulate their thought processes, track their progress, and critically examine their own CT, it is deeply personal and pedagogically assessable as an important foundation for students' long-term intellectual growth.

9. Conclusions

9.1. Introduction

This chapter presents a comprehensive summary of the project, by firstly highlighting its key contributions education field and discussing its limitations, by revisiting the initial aims and research questions, the chapter not only synthesises how the 7E IBL model functions in fostering CT among secondary school students, but also critically reflects on its broader applicability and potential for wider implementation., a brief overview of the research process and core findings, a discussion of limitations and recommendations for future research will be provided, drawn from the study's main threads.

9.2. Contribution to knowledge

Regarding the contribution to knowledge, this project offers several contributions across educational theory, empirical research, and classroom practice. Building on the foundations of the 7E Learning Cycle Model and Inquiry-based Learning method, the project developed an integrated instructional model (the 7E IBL model) through a process of pedagogical synthesis and innovation. The 7E IBL model addresses the gap in STEAM education (particularly within integrated STEAM education contexts) where there is a lack of unified and systematic teaching frameworks. It also contributes to a deeper theoretical understanding of multi-model integration in educational research. Meanwhile, the study further highlights the distinctive value of integrating multiple pedagogical models in the development of students' CT. It argues that the cultivation of CT skills and dispositions, since there is no correlation between them, cannot rely on a single teaching approach but requires a framework that draws on the strengths of different models to provide comprehensive support. As a result, this perspective introduces a new approach to the structured development of CT and lays a theoretical foundation for advancing other forms of higher-order thinking, such as creative thinking. Finally, by applying the new integrated model in STEAM education, the study demonstrates the feasibility and pedagogical potential of cross-model integration in achieving complex instructional goals.

From an empirical perspective, this intervention study provides evidence that the 7E IBL model can effectively support the development of students' CT, particularly in CT dispositions.

Meanwhile, this project also provides empirical evidence that there is no significant correlation between students' CT skills and dispositions, suggesting that the two may develop separately or through an integrated pedagogical model, rather than along a single typical trajectory. This finding also challenges the widely held notion that CT skills and dispositions have a positive correlation. Instead, it highlights the necessity of conceptualising CT skills and dispositions as parallel but distinct constructs, each requiring deliberate and differentiated attention within STEAM education.

The results point to the possibility that CT skills and dispositions follow different developmental pathways. As such, they should be treated as distinct yet equally important goals in educational planning. On the other hand, it offers empirical support to existing theoretical discussions and cautions against treating CT skills and dispositions as interchangeable in the design of instructional interventions. Moreover, while the increase in CT skills Overall scores was limited, individual progress reported was observed in some students. Thus, the development of CT skills may not occur uniformly, highlighting the value of recognising its non-linear and personalised nature.

Finally, the practical contribution of this study highlights the potential of an integrated model within the highly hands-on STEAM education to cultivate students' CT and other aspects, such as students building a strong and coherent subject knowledge system. It offers a workable theoretical framework for teachers and curriculum designers seeking to implement such models in practice. The findings suggest that the success of instructional interventions depends not only on the design logic of the model itself, but also on factors such as preparation, intention, and teacher-related variables. First, differences in teacher enactment play a noticeable role in shaping student outcomes. These differences are closely tied to teachers' conceptions of CT specifically, whether they recognise its value and educational relevance, which in turn affects their willingness to adopt the model and their effectiveness in implementing it in the classroom. Second, the study also highlights certain limitations in the development of students' CT skills. These may be linked to the intensity of the intervention, the limited instructional time available, and the inherently long-term nature of CT skills development. In other words, the model's effectiveness and sustainability are not determined by design alone; they also rely heavily on teachers' professional understanding, beliefs, and capacity to enact the model in practice, as

well as on sufficient preparation and appropriate allocation of time during implementation. Therefore, when promoting new instructional models, it is essential not only to optimise design features but also to invest in teacher training and professional development, improve the quality of intervention planning, and extend or phase the duration of implementation. These measures are key to ensuring both the practical relevance and long-term viability of such models across varied educational contexts.

In summary, this study proposed and substantiated a new instructional model from a theoretical perspective, and it also provided empirical evidence supporting the development of CT skills and dispositions. It offered fresh insights into STEAM education, teaching, and teacher development. Its overall contribution established a sustainable, model-integrated pathway for the systematic cultivation of students' CT skills and dispositions.

9.3. Limitations

This study has two main limitations. Firstly, it was conducted at one secondary school, which restricts the extent to which the findings can be applied to all school contexts. A second school was included in the first year of the project for comparison, involving one teacher and 30 students. The first site (the participating school) was a Band 1 school, where students tend to focus more on academic achievement. The second, a Band 2 school, served students with a more substantial interest in practical skills. However, unexpected changes to the course schedule at the second school meant that only half of the students received STEAM instruction in the first semester, while the others were scheduled for the second semester. This made it difficult to maintain a consistent control group. As a result, the second school was removed from the final study design. Although the lack of a comparative school is a limitation, a control group is present in the selected school, and the selected school reflects common characteristics of Band 1 public schools in Hong Kong. Therefore, the findings still offer insight that may be relevant to similar school contexts.

The sample size for CT skills ($n = 26$) was relatively small compared to that for CT dispositions ($n = 63$). Initially, 44 post-tests were collected from the experimental group. However, due to strict data-cleaning criteria (refer to chapter 4.6.2 for more details on the data-cleaning criteria),

several responses were excluded. For example, incomplete tests and those completed in an unusually short time were removed. Based on pilot testing, it typically takes 25 to 35 minutes for secondary students to complete the assessment. Therefore, responses completed in under 20 minutes were considered unreliable and excluded. In the end, 26 valid responses were retained for analysis. The researcher chose to retain only high-quality data, even though the comparatively small sample would have reduced the analysis's statistical power and potentially led to the undetected presence of modest effects. The trustworthiness of the data was more important to the researcher than increasing the sample size. In the context of an exploratory intervention, a smaller but cleaner dataset can still offer meaningful insights into the potential effects of the model. Moreover, the transparency and rigour of the data-cleaning process strengthen the credibility of the findings.

9.4. Future study

Despite these limitations, the study offers valuable insights into how the 7E LC model, and the IBL approach can be combined. The 7E IBL model seeks to develop students' CT in STEAM education and establishes the groundwork for longer-term, more extensive studies. Addressing the research limitations may be the main goal of future investigations. Firstly, comparison studies could be considered, which should expand the participating schools not only in Asia but also in Europe, to explore the impact of the 7E IBL model on students' CT in different education systems and student backgrounds. Alternatively, to find out if the new model has a different degree of impact on pupils, repeat the study in Hong Kong across several bands (1–3) or perform a cross-regional comparison. On the one hand, adding more data points to the study to make it a comparative study would allow for a more thorough analysis, perhaps using cluster analysis. On the other hand, incorporating motivational strategies during the test administration phase may help increase students' participation, and it could improve the participation in pre- and post-tests, thereby reducing sample attrition. Besides this, using segmented assessments or computer/phone-based testing formats to minimise student fatigue is a potential way of enhancing the completeness and quality of the data. Meanwhile, future exploration of the 7E IBL model's other impact on students, such as academic performance and creative skills, might be valuable. Lastly, as this study offers insightful information about data that can help other researchers improve the quality of intervention studies, where teacher engagement may be another important factor influencing intervention studies.

9.5. Implications

9.5.1. Theoretical implications

9.5.1.1. Theoretical implication of the 7E IBL model and the expansion on integrated educational pedagogical model

This study demonstrates that the 7E IBL model had a positive impact on the development of students' CT, particularly in CT dispositions. The findings suggest that the cultivation of students' CT depends not only on the content and strategies of instructional activities, but also on the structure and internal logic of the instructional model itself. As an intergrade model, the 7E IBL offers a pathway to increase students' CT, and its successful implementation systematically suggests that future instructional models do not need to be confined to a single theoretical framework or fixed paradigm. Instead, cross-model integration may enhance explanatory power at the theoretical level while improving adaptability to complex teaching environments in practice, particularly in interdisciplinary settings and in the development of higher-order thinking skills. Looking ahead, more attention should be given to the potential complementarity between different models, as well as to how their combined use might support the construction of structured knowledge, stimulate learner motivation, and promote the growth of critical and creative thinking. This perspective not only expands the theoretical understanding of instructional model design but also offers a valuable direction for developing more adaptable and sustainable teaching frameworks.

Meanwhile, the finding of no correlation of CT skills and dispositions implies that cultivating students' CT dispositions in STEAM education requires strategies that go beyond skills training. Teachers should focus on creating an encouraging, open-minded, and reflective classroom culture. As shown in the 7E IBL model, activities such as guided self-reflection, value-oriented discussions, and open-ended questioning give students meaningful opportunities to engage critically with content and ideas. The CT dispositions develop over time by consistent reinforcement in learning environments that place genuine value on inquiry and reflection. In contrast, CT skills are more effectively developed through structured and purposeful practice embedded in specific learning tasks. As a teaching strategy, the 7E IBL model incorporates a number of techniques (including argument analysis, logical reasoning, evidence-based thinking, and cooperative problem-solving) that allow students to use these abilities in the classroom. Teachers must therefore make a distinction between CT skills and dispositions. A student may

be open to questioning assumptions without having the analytical tools to do so, just as a technically skilled student may lack the disposition to apply those abilities in thoughtful ways. Recognising this distinction enables educators to better support individual learners by providing cognitive scaffolding where skills need development and encouraging reflection where dispositions are less well-formed.

9.5.1.2. Theoretical implication for teacher engagement in model design

Participating teachers play an important role in determining their effectiveness as the direct implementers of instructional interventions. The depth of teachers' understanding of CT, the degree of belief alignment, and their professional capacity all directly affect the impact of interventions in real classrooms. No matter how sophisticated a teaching model may be, it is unlikely to achieve its intended outcomes without genuine teacher buy-in and accurate implementation. On the contrary, when teachers show a clear understanding of the pedagogical rationale and are equipped with the necessary support and conditions for professional development, their classroom practices are more likely to generate positive and sustainable outcomes. For example, in this project, throughout the intervention process, the researcher not only focused on designing and optimising course content but also continuously cooperated and communicated with teachers, actively responding to their actual needs and challenges. Only by supporting teachers to move from passive executors to active practitioners and members of a pedagogical community can the value of instructional interventions take root and bring about meaningful, long-term improvements in students' cognitive and thinking dispositions. On the contract, without the belief of the users, the teachers, it would be hard for any intervention to show its real effect. This realisation has a theoretical ramification for the construction of instructional models: instead of regarding participating teachers as invisible implementers, future models should take teacher-related elements into account as active variables.

9.5.2. Practical implications

9.5.2.1. For teachers and lesson designers:

A few essential requirements must be fulfilled in order to guarantee that the 7E IBL model can be applied successfully in practice and actually aid in the growth of students' CT. Teachers must first have time to get ready before implementing the model. A clear grasp of each stage and

growing confidence in adapting it to real classroom situations enable teachers to make better instructional choices and respond more thoughtfully to students' learning needs. Without this preparation, the model may lose its intended flexibility and become challenging to use effectively. Second, the kinds of learning tasks built around the model matter. Activities that are rooted in real-world contexts and structured to encourage layered thinking tend to do more than hold students' interest; they help create the conditions needed for CT to take shape. In addition, students benefit when inquiry is not only encouraged but actively guided. Opportunities to explore ideas independently, collaborate with peers, respond to well-timed teacher questions, and reflect on what they have learned all play a role in helping them develop more lasting habits of mind. These are not just optional techniques; they form the core of how the model can support deeper thinking in everyday practice.

Hence, from a practical perspective, this study also demonstrates that the 7E IBL model offers a potentially high degree of flexibility and adaptability in real classroom settings. Although originally developed and implemented in the context of integrated STEAM education, the model is not limited to STEAM subjects. It can be applied, either in whole or in part, across a range of subject areas, including traditional science disciplines like mathematics, physics, and engineering, as well as humanities subjects. For instance, one of the four participating teachers adopted elements of the 7E IBL model, specifically the "elicit" and "extend" stages, in a history class he also taught. This adaptation helped students build a more structured and transferable understanding of historical knowledge. The most exciting part was that he introduced the notebook component, which was initially used as a learning journal in the model, to other history teachers. It was well received and later adopted across the school's entire history curriculum. This example shows that while full adoption of the model is encouraged, teachers can also adapt selected components in ways that suit their subject areas and teaching styles.

Finally, the new model's staged structure allows for flexible application, rather than requiring a fixed sequence. It might be more feasible to divide the model across two or more lessons in disciplines with shorter class durations, usually lasting 30 to 45 minutes, as opposed to the about 60 minutes in STEAM programs. For instance, in order to preserve the integrity of the model, teachers may decide to use the entire model throughout several lessons on the same subject. Aim to reduce teachers' pressure to fit all elements of the 7E IBL model into a single

class. Overall, the adaptability of the 7E IBL model provides teachers with more flexibility to make decisions that align with their classroom realities, enabling them to design lessons that are both structured and responsive to diverse teaching contexts.

9.5.2.2. For researchers:

Although the impact of the 7E IBL model on the development of students' CT skills appeared limited within the timeframe of a single-semester intervention, upward trends across several indicators suggest that the model had begun to take effect. As one of the higher-order skills, CT skills are complex and tend to develop gradually over time. Instead of brief exposure, their maturation frequently necessitates consistent, purposeful instructional guidance. The lack of model efficacy may not be the cause of the nonsignificant statistical increase for CT skills in this project; rather, it emphasises the need for more thorough research methods that may accurately reflect the developmental nature of CT skills.

Extending the intervention period to two semesters or even a full academic year could offer a more suitable window to observe measurable growth and deeper internalisation of CT processes. Importantly, this prolonged period should not be viewed as idle time but rather as a dynamic and iterative period of cognitive engagement, involving deliberate effort on the part of teachers, regular student participation, and, more generally, a school culture that values in-depth learning over superficial performance. To fully realise the potential of the 7E IBL model in supporting CT, there must be a strong alignment between teaching strategies, learning goals, and the pace at which students develop cognitively. A longer-term study would help reveal how this alignment evolves over time and under what conditions it yields the most meaningful impact.

9.6. Overall

Overall, as shown in the table below, one semester-long teaching intervention based on the 7E IBL model had a positive impact on both CT skills and dispositions (excluding the curiosity metrics) among secondary school students in the context of STEAM education. Notably, there was a statistically significant increase in students' CT dispositions overall scores. Although the overall test results for CT skills did not reach statistical significance, both the upward trends

across every metric and the findings from qualitative analyses suggest a clear trajectory of improvement. Additionally, there is no correlation between CT skills and disposition; therefore, these two should be cultivated separately or through an integrated teaching model.

Three interconnected and mutually supporting features of the 7E IBL model are responsible for its success in developing students' CT abilities and dispositions. First, the model integrates structured scaffolding of new abilities and systematic review of existing information before each inquiry activity. At the conclusion of the session, there is a reflective consolidation of the main ideas. This pedagogical sequence builds a clear, progressive disciplinary knowledge system, laying a solid foundation for students' ongoing knowledge construction and skill development. Secondly, drawing on constructivist theories, particularly those of Vygotsky, the model promotes dialogic teaching supported by Socratic questioning and collaborative problem solving among students. Teachers led students through multi-level, scaffolded conversations that necessitate cooperation and consistent communication in authentic learning environments. Students can develop more sophisticated and flexible CT skills over time by honing and deepening their perspectives through this iterative process of articulation and reflection. As seen by the obvious improvement in their CT dispositions, the effective and captivating inquiry process also fosters students' curiosity and intrinsic drive, which in turn promotes more active learning behaviours and builds their self-confidence in their ability to learn. Lastly, the paradigm consistently incorporates structured near-transfer tasks of suitable complexity in both the inquiry and extension phases. These tasks force students to reorganise and reinterpret preexisting cognitive structures by requiring them to apply learnt material in novel but comparable circumstances. Because of this, rote memorisation alone is no longer enough, and metacognitive processes are triggered. Metacognition is triggered, starting a dynamic cognitive loop that allows CT to perform analysis, planning, and evaluation. Students' comprehension of the subject matter is further improved via reflective feedback. During the Inquiry activity itself, the Elaborate task during the inquiry phase, and the Extension task at the end of the lesson, this cycle of "metacognitive activation – CT engagement – reflective feedback" usually occurs at least three times in a single lesson. Accordingly, the model supports students' CT development through its integrated design, which brings together three essential elements in each session: a coherent and well-structured knowledge base, an engaging and intellectually demanding inquiry process, and the iterative integration of dynamic cognitive training. These elements

work together to create a long-lasting and efficient feedback loop that gradually and significantly improves students' ability to develop CT skills and dispositions.

References

- Abrami, P. C., Bernard, R. M., Borokhovski, E., Waddington, D. I., Wade, C. A., & Persson, T. (2015). Strategies for Teaching Students to Think Critically: A Meta-Analysis. *Review of educational research, 85*(2), 275-314.
<https://doi.org/10.3102/0034654314551063>
- agency, C. S. o. n. (2021). *The Outline of China the 14th Five Year Plan (2021-2025) and the Vision for 2035*. CHINA'S official news agency.
http://www.npc.gov.cn/npc/c2/kgfb/202103/t20210313_310753.html
- Ahmed, W., & Mudrey, R. R. (2019). The role of motivational factors in predicting STEM career aspirations. *International Journal of School & Educational Psychology, 7*(3), 201-214.
- Argote, L., & Ingram, P. (2000). Knowledge Transfer: A Basis for Competitive Advantage in Firms. *Organizational behavior and human decision processes, 82*(1), 150-169.
<https://doi.org/10.1006/obhd.2000.2893>
- Arifin, Z., Saputro, S., & Kamari, A. (2025). The effect of inquiry-based learning on students' critical thinking skills in science education: A systematic review and meta-analysis. *Eurasia Journal of Mathematics, Science and Technology Education, 21*(3), em2592.
- Arksey, H., & Knight, P. T. (1999). Interviewing for social scientists: An introductory resource with examples.
- Artino, A. R., Jr, & Konopasky, A. (2018). The Practical Value of Educational Theory for Learning and Teaching in Graduate Medical Education. *Journal of Graduate Medical Education, 10*(6), 609-613.
- Atkin, J. M., & Karplus, R. (1962). Discovery or invention? *The science teacher, 29*(5), 45-51.
- Ausubel, D. P. (1963). The psychology of meaningful verbal learning.
- Ausubel, D. P. (1968). A Cognitive view. *Educational psychology*.
- Bandura, A., & Walters, R. H. (1977). *Social learning theory* (Vol. 1). Prentice hall Englewood Cliffs, NJ.
- Barnes, B., & Payette, P. (2017). Socratic Questioning. *The National teaching & learning forum, 26*(6), 6-8. <https://doi.org/10.1002/ntlf.30129>
- Barnett, S. M., & Ceci, S. J. (2002). When and where do we apply what we learn?: A taxonomy for far transfer. *Psychological bulletin, 128*(4), 612.
- Barrows, H. S., & Tamblyn, R. M. (1980). *Problem-based learning: An approach to medical education*. Springer Publishing Company.
- Beker, K. (2008). Learning from texts: extending and revising knowledge. *Cognition, 19*, 1061-1070.
- Bereiter, C., & Scardamalia, M. (2013). *The psychology of written composition*. Routledge.
- Bertrand, M. G., & Namukasa, I. K. (2023). A pedagogical model for STEAM education. *Journal of research in innovative teaching & learning, 16*(2), 169-191.
<https://doi.org/10.1108/JRIT-12-2021-0081>
- Birt, L., Scott, S., Cavers, D., Campbell, C., & Walter, F. (2016). Member checking: a tool to enhance trustworthiness or merely a nod to validation? *Qualitative health research, 26*(13), 1802-1811.
- Bowell, T., Cowan, R., & Kemp, G. (2020). Critical Thinking: A concise guide, 5th Edn. In: Routledge New York, NY.
- Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative research in psychology, 3*(2), 77-101. <https://doi.org/10.1191/1478088706qp063oa>

- Brod, G., Werkle-Bergner, M., & Shing, Y. L. (2013). The influence of prior knowledge on memory: a developmental cognitive neuroscience perspective. *Frontiers in behavioral neuroscience*, 7, 139.
- Brown, J. S., Collins, A., & Duguid, P. (1989). Situated cognition and the culture of learning. *1989*, 18(1), 32-42.
- Bruner, J. S. (1961). The act of discovery. *Harvard educational review*.
- Bybee, R. W. (1990). Science for life & living: An elementary school science program from biological sciences curriculum study. *The American Biology Teacher*, 52(2), 92-98.
- Bybee, R. W. (1997). *Achieving scientific literacy: From purposes to practices*. ERIC.
- Bybee, R. W., Taylor, J. A., Gardner, A., Van Scotter, P., Powell, J. C., Westbrook, A., & Landes, N. (2006). The BSCS 5E instructional model: Origins and effectiveness. *Colorado Springs, Co: BSCS*, 5(88-98).
- Bónus, L., & Antal, E. (2021). Innovative Inquiry-based Methods in Learning and Teaching Science. *Journal of Studies in Education*, 11(3), 1-22.
- CECR, C. A. o. E. S. (2019). *中国STEM 教育调研报告, 简要版*
- Chen, X. (2000). *Qualitative research in social sciences*. Beijing Educational Science Publishing.
- Chin, C., & Osborne, J. (2008). Students' questions: a potential resource for teaching and learning science. *Studies in science education*, 44(1), 1-39.
- China, M. o. E. o. t. P. s. R. o. (2021). *The Outline of China the 14th Five Year Plan (2021-2025) and the Vision for 2035*. CHINA'S official news agency. http://www.npc.gov.cn/npc/c2/kgfb/202103/t20210313_310753.html
- China., M. o. E. o. t. P. s. R. o. (2015). *Notice from the General Office of the Ministry of Education Regarding Soliciting Opinions on the 'Guiding Opinions on Comprehensively and Thoroughly Advancing Education Informatisation During the 13th Five-Year Plan Period (Draft for Comment)'* 教育部办公厅关于征求对《关于“十三五”期间全面深入推进教育信息化工作的指导意见（征求意见稿）》意见的通知. http://www.moe.gov.cn/srcsite/A16/s3342/201509/t20150907_206045.html
- China., M. o. E. o. t. P. s. R. o. (2016a). Core Competencies and Values for Chinese Students' Development. *China Academic Journal*, 1-3.
- China., M. o. E. o. t. P. s. R. o. (2016b). Core Competencies and Values for Chinese Students' Development. 中国学生发展核心素养。 . *China Academic Journal*, 1-3.
- China., M. o. E. o. t. P. s. R. o. (2016c). *Notice on issuing the "13th Five-Year Plan for Education Informatization"* 教育部关于印发《教育信息化“十三五”规划》的通知. http://www.moe.gov.cn/srcsite/A16/s3342/201606/t20160622_269367.html
- China., M. o. E. o. t. P. s. R. o. (2022). *Compulsory Education Curriculum Reform. 义务教育课程方案（2022年版）*. B. N. U. P. Group. chrome-extension://efaidnbmnmbnibpcajpcglclefindmkaj/<https://www.gov.cn/zhengce/zhengceku/2022-04/21/P020231110625849851424.pdf>
- Choy, S. C., & Cheah, P. K. (2009). Teacher Perceptions of Critical Thinking among Students and Its Influence on Higher Education. *International journal of teaching and learning in higher education*, 20(2), 198.
- Clark, R. E., Kirschner, P. A., & Sweller, J. (2012). Putting students on the path to learning: The case for fully guided instruction. *American educator*, 36(1), 6-11.
- Cohen, J. (2013). *Statistical power analysis for the behavioral sciences*. routledge.
- Cohen, L. (2017). *Research Methods in Education*.

- Cohen, L., Manion, L., & Morrison, K. (2002). *Research methods in education*. routledge.
- Collins, A., & Stevens, A. L. (1983). A cognitive theory of inquiry teaching. *Instructional-design theories and models: An overview of their current status, 1*.
- Cook, T. D., Campbell, D. T., & Day, A. (1979). *Quasi-experimentation: Design & analysis issues for field settings* (Vol. 351). Houghton Mifflin Boston.
- Creswell, J. (2014). *Research design: qualitative, quantitative, and mixed methods approaches*.
- Crouch, C. H., & Mazur, E. (2001). Peer Instruction: Ten years of experience and results. *American journal of physics*, 69(9), 970-977. <https://doi.org/10.1119/1.1374249>
- CSEDS, C. S. o. E. D. S. (2024). *STEM Education 2035 Action Plan*. China Science Education Research Centre. <https://stem.zjnu.edu.cn/2024/0803/c13414a473551/page.htm>
- Curran, P. G. (2016). Methods for the detection of carelessly invalid responses in survey data. *Journal of Experimental Social Psychology*, 66, 4-19.
- Dana, N. F., Thomas, C., & Boynton, S. (2011). *Inquiry: A districtwide approach to staff and student learning*. Corwin Press.
- Darling-Hammond, L., Hyler, M. E., & Gardner, M. (2017). Effective teacher professional development. *Learning policy institute*.
- Delić, H., & Bećirović, S. (2016). Socratic method as an approach to teaching. *European Researcher. Series A*(10), 511-517.
- Desimone, L. M. (2009). Improving Impact Studies of Teachers' Professional Development: Toward Better Conceptualizations and Measures. *Educational researcher*, 38(3), 181-199. <https://doi.org/10.3102/0013189X08331140>
- Deslauriers, L., Schelew, E., & Wieman, C. (2011). Improved Learning in a Large-Enrollment Physics Class. *Science (American Association for the Advancement of Science)*, 332(6031), 862-864. <https://doi.org/10.1126/science.1201783>
- Dewey, J. (1938). *Experience & Education*. Kappa Delta Pi, New York.
- Dong, Y. P., Jingda; He, Jiaxin; Lin, Suiyi; Yu, Hongjing; Ling, Donglan. (2024). A concept analysis of reflective practice in nurses. *China Nursing Journal*, 59(1), 124-129. <https://doi.org/10.3761/j.issn.0254-1769.2024.01.017>
- Duran, L. B., & Duran, E. (2004). The 5E instructional model: A learning cycle approach for inquiry-based science teaching. *Science Education Review*, 3(2), 49-58.
- EDB, E. B., The Government of the Hong Kong Special Administrative Region of the People's Republic of China (2015a). Policy Address.
- EDB, E. B., The Government of the Hong Kong Special Administrative Region of the People's Republic of China (2015b). *Promoting STEM Education-Report on Unleashing Creative Potential. 推动STEM教育·发挥创意潜能概览*. chrome-extension://efaidnbmninnibpcapjpcglclefindmkaj/[https://www.edb.gov.hk/attachment/tc/curriculum-development/renewal/Brief%20on%20STEM%20\(Overview\)_chi_20151105.pdf](https://www.edb.gov.hk/attachment/tc/curriculum-development/renewal/Brief%20on%20STEM%20(Overview)_chi_20151105.pdf)
- EDB, E. B., The Government of the Hong Kong Special Administrative Region of the People's Republic of China (2022). Policy Address.
- EDB, E. B., The Government of the Hong Kong Special Administrative Region of the People's Republic of China (2023). Policy Address.
- EDB, E. B., The Government of the Hong Kong Special Administrative Region of the People's Republic of China (2024). Policy Address.
- Eisenkraft, A. (2003). Expanding the 5E model. *The science teacher*, 70(6), 56.
- ETS, E. T. S. (2015). *HEIghten critical thinking assessment*. https://www.ets.org/heighten/about/critical_thinking/

- Facione, P. (1990). Critical thinking: A statement of expert consensus for purposes of educational assessment and instruction (The Delphi Report).
- Facione, P. A., Facione, N. C., & Giancarlo, C. A. F. (2000). *The California critical thinking disposition inventory: CCTDI test manual*. California Acad. Press.
- Falloon, G., Hatzigianni, M., Bower, M., Forbes, A., & Stevenson, M. (2020). Understanding K-12 STEM Education: a Framework for Developing STEM Literacy. *Journal of science education and technology*, 29(3), 369-385. <https://doi.org/10.1007/s10956-020-09823-x>
- Fawkes, D., O'meara, B., Weber, D., & Flage, D. (2005). Examining the exam: A critical look at the California Critical Thinking Skills Test. *Science & Education*, 14(2), 117-135.
- Field, A. (2024). *Discovering statistics using IBM SPSS statistics*. Sage publications limited.
- Finn, B. (2015). Measuring motivation in low-stakes assessments. *ETS Research Report Series*, 2015(2), 1-17.
- Fiorella, L., & Mayer, R. E. (2016). Eight ways to promote generative learning. *Educational psychology review*, 28(4), 717-741.
- Flavell, J. H. (1971). First discussant's comments: What is memory development the development of? *Human development*, 14(4), 272-278.
- Flavell, J. H. (1979). Metacognition and cognitive monitoring: A new area of cognitive-developmental inquiry. *American psychologist*, 34(10), 906.
- Furtak, E. M., & Ruiz-Primo, M. A. (2008). Making students' thinking explicit in writing and discussion: An analysis of formative assessment prompts. *Science Education*, 92(5), 799-824.
- Furtak, E. M., Seidel, T., Iverson, H., & Briggs, D. C. (2012). Experimental and quasi-experimental studies of inquiry-based science teaching: A meta-analysis. *Review of educational research*, 82(3), 300-329.
- Goodchild, S., Fuglestad, A. B., & Jaworski, B. (2013). Critical alignment in inquiry-based practice in developing mathematics teaching. *Educational Studies in Mathematics*, 84(3), 393-412.
- Grancharova, D. (2024a). Innovating STEM education: Teacher reflections on challenges, strategies, and development. *International Journal of Emerging Trends in Social Sciences*, 17(2), 37-45. <https://doi.org/10.55217/103.v17i2.836>
- Grancharova, D. (2024b). Innovating STEM education: Teacher reflections on challenges, strategies, and development. *International Journal of Emerging Trends in Social Sciences*, 37-45. <https://doi.org/10.55217/103.v17i2.836>
- Guan, W., & Cai, J. (2018). 上海市中小学 STEM 教育调研报告. 上海科技教育出版社, 4.
- Guan Wenchuan, & Jie, C. (2018). 上海市中小学 STEM 教育调研报告. 上海科技教育出版社, 4.
- Guskey, T. R. (2002). Professional development and teacher change. *Teachers and teaching*, 8(3), 381-391.
- Halpern, D. F. (2014). *Critical thinking across the curriculum: A brief edition of thought & knowledge*. Routledge.
- Halpern, D. F. (2014). *Thought and knowledge: an introduction to critical thinking* (Fifth ed.). Psychology Press, Taylor & Francis Group. <https://doi.org/10.4324/9781315885278>
- He, S. (2019). *The influence on critical thinking disposition of junior high school students in learning STEM curriculum* (Publication Number 50) Hangzhou Normal University]. China Academic Journal Electronic Publishing House.
- Heindl, M. (2019). Inquiry-based learning and the pre-requisite for its use in science at school: A meta-analysis. *Journal of Pedagogical Research*, 3(2), 52-61.

- Heindl, M. (2020). An Extended Short Scale for Measuring Intrinsic Motivation When Engaged in Inquiry-Based Learning. *Journal of Pedagogical Research*, 4(1), 22-30.
- Hmelo-Silver, C. E., Duncan, R. G., & Chinn, C. A. (2007). Scaffolding and achievement in problem-based and inquiry learning: a response to Kirschner, Sweller, and. *Educational psychologist*, 42(2), 99-107.
- Hofer, E., Abels, S., & Lembens, A. (2018). Inquiry-based learning and secondary chemistry education-a contradiction? *Research in Subject-matter Teaching and Learning (RISTAL)*, 1(2018), 51-65.
- Hofstein, A., & Lunetta, V. N. (2004). The laboratory in science education: Foundations for the twenty-first century. *Science education*, 88(1), 28-54.
- Hou, Y. (2022). Reflections on the applicability of critical thinking measurements in the Chinese context. *Journal of East China Normal University*, 40(2), 25-34. (Educational Sciences Edition)
- Hu, H.-W., Chiu, C.-H., & Chiou, G.-F. (2019). Effects of question stem on pupils' online questioning, science learning, and critical thinking. *The Journal of Educational Research*, 112(4), 564-573.
- Huang, J. L., Curran, P. G., Keeney, J., Poposki, E. M., & DeShon, R. P. (2012). Detecting and deterring insufficient effort responding to surveys. *Journal of Business and Psychology*, 27(1), 99-114.
- Ibrahim, A., Aulls, M. W., & Shore, B. M. (2017). Teachers' roles, students' personalities, inquiry learning outcomes, and practices of science and engineering: The development and validation of the McGill attainment value for inquiry engagement survey in STEM disciplines. *International Journal of Science and Mathematics Education*, 15(7), 1195-1215.
- Jainal, S., & Yosephine Louise, I. S. (2019). Macromedia Flash Based on Guided Inquiry in Critical Thinking Skills as Learning Innovations. *Online Submission*, 10(3), 21-29.
- Jiwei, Z. (2024). Textual Analysis of STEM Education Policies at the Basic Education Stage- Based on the policy tool perspective.
- Karplus, R., & Thier, H. D. (1967). A new look at elementary school science: Science curriculum improvement study. (*No Title*).
- Keeves, J. (2004). *Educational Research, methodologies, and measurement: An international handbook*.
- Keeves, J. P. (1990). *Educational research, methodology, and measurement: An international handbook*. Pergamon press.
- Keselman, A. (2003). Supporting inquiry learning by promoting normative understanding of multivariable causality. *Journal of Research in Science Teaching*, 40(9), 898-921.
- Keys, C. W., Hand, B., Prain, V., & Collins, S. (1999). Using the science writing heuristic as a tool for learning from laboratory investigations in secondary science. *Journal of research in science Teaching*, 36(10), 1065-1084.
- Kirschner, P., Sweller, J., & Clark, R. E. (2006). Why unguided learning does not work: An analysis of the failure of discovery learning, problem-based learning, experiential learning and inquiry-based learning. *Educational psychologist*, 41(2), 75-86.
- KOFAC, K. F. f. t. A. o. S. a. C. (2016). *Introduction to STEAM education*. https://steam.kofac.re.kr/?page_id=11269.
- Kong, E. B. o. H. (2016). *Report on Promotion of STEM Education: Unleashing potential in innovation*. https://www.edb.gov.hk/attachment/en/curriculum-development/renewal/STEM%20Education%20Report_Eng.pdf
- Konrad, M., Joseph, L. M., & Eveleigh, E. (2009). A meta-analytic review of guided notes. *Education and Treatment of Children*, 32(3), 421-444.

- Ku, K. Y. L., & Ho, I. T. (2010). Metacognitive strategies that enhance critical thinking. *Metacognition and learning*, 5(3), 251-267. <https://doi.org/10.1007/s11409-010-9060-6>
- Kuhn, D. (1999). A Developmental Model of Critical Thinking. *Educational researcher*, 28(2), 16-46. <https://doi.org/10.3102/0013189X028002016>
- Lai, E. R. (2011). Critical thinking: A literature review. *Pearson's research reports*, 6(1), 40-41.
- Lakens, D. (2013). Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs. *Frontiers in psychology*, 4, 863.
- Lin, C.-L., & Tsai, C.-Y. (2021). The effect of a pedagogical STEAM model on students' project competence and learning motivation. *Journal of Science Education and Technology*, 30(1), 112-124.
- Liu, Y., & Pásztor, A. (2022). Effects of problem-based learning instructional intervention on critical thinking in higher education: A meta-analysis. *Thinking skills and creativity*, 45, 101069. <https://doi.org/10.1016/j.tsc.2022.101069>
- Loeser, J. W. (2013). Differentiated instruction. *Research Starters: Education*.
- Lu, Y.-Y., Lin, H.-s., Smith, T. J., Hong, Z.-R., & Hsu, W.-Y. (2020). The Effects of Critique-Driven Inquiry Intervention on Students' Critical Thinking and Scientific Inquiry Competency. *Journal of Baltic Science Education*, 19(6), 954-971.
- Maguire, M., & Delahunt, B. (2017). Doing a thematic analysis: A practical, step-by-step guide for learning and teaching scholars. *All Ireland journal of higher education*, 9(3).
- Maknun, J. (2020). Implementation of Guided Inquiry Learning Model to Improve Understanding Physics Concepts and Critical Thinking Skill of Vocational High School Students. *International Education Studies*, 13(6), 117-130.
- Marfilinda, R., Rossa, R., Jendriadi, J., & Apfani, S. (2020). The effect of 7e learning cycle model toward students' learning outcome of basic science concept. *Journal of teaching and learning in Elementary Education*, 3(1), 77-87.
- Margot, K. C., & Kettler, T. (2019). Teachers' perception of STEM integration and education: a systematic literature review. *International Journal of STEM Education*, 6(1), 1-16. <https://doi.org/10.1186/s40594-018-0151-2>
- Marzano, R. J. (2004). *Building background knowledge for academic achievement: Research on what works in schools*. Ascd.
- Mazur, E. (1997). *Peer instruction: a user's manual*. Prentice Hall.
- McComas, W. F., & Olson, J. K. (1998). The nature of science in international science education standards documents. In *The nature of science in science education: Rationales and strategies* (pp. 41-52). Springer.
- McDermott, M. A., & Hand, B. (2013). The impact of embedding multiple modes of representation within writing tasks on high school students' chemistry understanding. *Instructional Science*, 41(1), 217-246.
- Meade, A. W., & Craig, S. B. (2012). Identifying careless responses in survey data. *Psychological methods*, 17(3), 437.
- Merton, R. K., & Kendall, P. L. (1946). The Focused Interview. *The American journal of sociology*, 51(6), 541-557. <https://doi.org/10.1086/219886>
- Morales-Martinez, G. E., Mezquita-Hoyos, Y. N., Hedlefs-Aguilar, M. I., & Sanchez-Monroy, M. (2021). Cognitive assessment of knowledge consolidation in a course on the diagnostic evaluation of learning disorders in psychology students. *International Journal of Learning, Teaching and Educational Research*, 20(10).
- Neuman, W. (2014). *Social research methods: qualitative and quantitative approaches*.
- NGSS, N. G. S. S. (2013). <https://www.nextgenscience.org/>

- Nicol, C., Gakuba, E., & Habinshuti, G. (2020). An overview of learning cycles in science inquiry-based instruction. *African Journal of Educational Studies in Mathematics and Sciences*, 16(2), 76-81.
- Nunes, T., Stylianides, G. J., Lea, R., & Matthews, L. (2024). Replication in educational interventions: developing a tool to measure and promote fidelity. *International journal of research & method in education*, 1-22. <https://doi.org/10.1080/1743727X.2024.2420336>
- Pahrudin, A., Alisia, G., Saregar, A., Asyhari, A., Anugrah, A., & Susilowati, N. E. (2021). The Effectiveness of Science, Technology, Engineering, and Mathematics Inquiry Learning for 15-16 Years Old Students Based on K-13 Indonesian Curriculum: The Impact on the Critical Thinking Skills. *European Journal of Educational Research*, 10(2), 681-692.
- Papagiannopoulou, T., & Vaiopoulou, J. (2024). Teachers' Attitudes Towards STEM Education: Exploring the Role of Their Readiness via a Structural Equation Model. *European journal of investigation in health, psychology and education*, 14(11), 2850-2864. <https://doi.org/10.3390/ejihpe14110187>
- Paul, R., & Elder, L. (2007). The Thinker's Guide to the Art of Socratic Questioning. Foundation for Critical Thinking. In: Recuperado el.
- Pcast, T. (2010). K-12 education in science, technology, engineering, and math (stem) for america's future. *President's Council of Advisors on Science and Technology*.
- Pedaste, M., Mäeots, M., Siiman, L. A., De Jong, T., Van Riesen, S. A., Kamp, E. T.,... Tsourlidaki, E. (2015). Phases of inquiry-based learning: Definitions and the inquiry cycle. *Educational research review*, 14, 47-61.
- Peng, M., Wang, G., & Chen, J. (2004). Validity and reliability of the Chinese critical thinking disposition inventory. *Chinese Journal of Nursing*, 39(9), 644-647.
- Perdana, R., & Rudibyani, R. B. (2020). The Effectiveness of Inquiry Social Complexity to Improving Critical and Creative Thinking Skills of Senior High School Students. *International Journal of Instruction*, 13(4), 477-490.
- Perignat, E., & Katz-Buonincontro, J. (2019). STEAM in practice and research: An integrative literature review. *Thinking skills and creativity*, 31, 31-43.
- Perkins, D. N., & Salomon, G. (1992). Transfer of learning. *International encyclopedia of education*, 2, 6452-6457.
- Perry, W. G., Jr., & Knefelkamp, L. (1999). *Forms of intellectual and ethical development in the college years: a scheme* (First ed.). Jossey-Bass, A Wiley Company.
- Piaget, J. (1977). The role of action in the development of thinking. In *Knowledge and Development: Volume 1 Advances in Research and Theory* (pp. 17-42). Springer.
- Piaget, J., & Cook, M. (1952). *The origins of intelligence in children* (Vol. 8). International universities press New York.
- Prince, M., Vigeant, M., & Nottis, K. (2012). Development of the heat and energy concept inventory: Preliminary results on the prevalence and persistence of engineering students' misconceptions. *Journal of Engineering Education*, 101(3), 412-438.
- Profetto-McGrath, J. (2003). The relationship of critical thinking skills and critical thinking dispositions of baccalaureate nursing students. *Journal of advanced nursing*, 43(6), 569-577. <https://doi.org/10.1046/j.1365-2648.2003.02755.x>
- Ren, C. (2014). How to Develop Students' Critical Thinking Skills among Inquiry-Based Activities. *Curriculum, Teaching Material and Method*, 34(11).
- Resnick, L. B., & Libertus, M. E., & Schantz, F. (2019). *The Routledge International Handbook of Research on Dialogic Education* (Vol. The future of dialogic education.).
- Ribeirinha, T., Baptista, M., & Correia, M. (2024). Investigating the Impact of STEM Inquiry-Based Learning Activities on Secondary School Student's STEM Career

- Interests: A Gender-Based Analysis Using the Social Cognitive Career Framework. *Education sciences*, 14(10), 1037. <https://doi.org/10.3390/educsci14101037>
- Rodriguez, A. J. (2015). What about a dimension of engagement, equity, and diversity practices? A critique of the next generation science standards. *Journal of research in science teaching*, 52(7), 1031-1051. <https://doi.org/10.1002/tea.21232>
- Roediger III, H. L., & Karpicke, J. D. (2006a). Test-enhanced learning: Taking memory tests improves long-term retention. *Psychological science*, 17(3), 249-255.
- Roediger III, H. L., & Karpicke, J. D. (2006b). The power of testing memory: Basic research and implications for educational practice. *Perspectives on psychological science*, 1(3), 181-210.
- Roehrig, G. H., & Kruse, R. A. (2005). The role of teachers' beliefs and knowledge in the adoption of a Reform-Based curriculum. *School science and Mathematics*, 105(8), 412-422.
- Runco, M. A. (2003). *Critical creative processes*. Hampton Press.
- Sam, R. (2024). Systematic review of inquiry-based learning: assessing impact and best practices in education. *F1000Research*, 13, 1045.
- Sampson, V., Grooms, J., & Walker, J. P. (2011). Argument-Driven Inquiry as a way to help students learn how to participate in scientific argumentation and craft written arguments: An exploratory study. *Science Education*, 95(2), 217-257.
- Schraw, G., & Dennison, R. S. (1994). Assessing Metacognitive Awareness. *Contemporary educational psychology*, 19(4), 460-475. <https://doi.org/10.1006/ceps.1994.1033>
- Schwab, J. J. (1960). Inquiry, the science teacher, and the educator. *The school review*, 68(2), 176-195.
- Schweingruber, H., Pearson, G., & Honey, M. (2014). *STEM integration in K-12 education: Status, prospects, and an agenda for research*. National Academies Press.
- Schön, D. A. (2017). *The reflective practitioner: How professionals think in action*. Routledge.
- Sciences., C. N. I. o. E. (2017). *China STEM education white paper*. 中国STEM教育白皮书
[chrome-extension://efaidnbmninnibpcajpcgclefindmkaj/http://www.ckjy.org/wp-content/uploads/2017/09/STEM%E6%95%99%E8%82%B2%E7%99%BD%E7%9A%AE%E4%B9%A6.pdf](http://www.ckjy.org/wp-content/uploads/2017/09/STEM%E6%95%99%E8%82%B2%E7%99%BD%E7%9A%AE%E4%B9%A6.pdf)
- Scriven, M., & Paul, R. (1987). Critical thinking. The 8th Annual International Conference on Critical Thinking and Education Reform, CA,
- Selwyn, N., & Facer, K. (2013). *The politics of education and technology: Conflicts, controversies, and connections*. Springer.
- Shadish, W. R., Cook, T. D., & Campbell, D. T. (2002). *Experimental and quasi-experimental designs for generalized causal inference*. Houghton, Mifflin and Company.
- Shen, L. (2018). *History of the development of inquiry-based learning*.
- Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. *Educational researcher*, 15(2), 4-14.
- Stanley, J. T., & Lewandowski, H. (2016). Lab notebooks as scientific communication: Investigating development from undergraduate courses to graduate research. *Physical Review Physics Education Research*, 12(2), 020129.
- Sujarwanto, E., & Sanjaya, I. (2021). A conceptual framework of STEM education based on the Indonesian Curriculum. *Journal of Physics: Conference Series*,
- Sullivan, T. N., Farrell, A. D., Sutherland, K. S., Behrhorst, K. L., Garthe, R. C., & Greene, A. (2021). Evaluation of the Olweus Bullying Prevention Program in US Urban Middle Schools Using a Multiple Baseline Experimental Design. *Prevention science*, 22(8), 1135. <https://doi.org/10.1007/s11121-021-01244-5>

- Tang, H. (2017). *Practical Research on Scientific Inquiry Micro Activities for the Development of Students' Critical Thinking*. Shanghai Normal University].
- Tengyue, Z. (2024). *2024 Research Report on Youth STEAM Education: Interdisciplinary Integration, Holistic Development, and Keeping Pace with the Times*. 2024 年青少年 STEAM 教育研究报告- 学科融合 · 综合培养 · 与时俱进 。
- Thibaut, L., Ceuppens, S., De Loof, H., De Meester, J., Goovaerts, L., Struyf, A.,...De Cock, M. (2018). Integrated STEM education: A systematic review of instructional practices in secondary education. *European Journal of STEM Education*, 3(1), 2.
- Thomas, J. W. (2000). A review of research on project-based learning. In: San Rafael, CA, USA.
- Thorndike, E. L. (1913). *The psychology of learning* (Vol. 2). Teachers College, Columbia University.
- Thorndike, E. L. (2013). *Education psychology: Briefer course*. Routledge.
- Todd, R., & Geoff, K. (2016). A conceptual framework for integrated STEM education. *International Journal of STEM Education*, 3(16), 134-149.
- Tseng, V. (2012). *The uses of research in policy and practice*. Society for Research in Child Development Washington, DC.
- Urdanivia Alarcon, D. A., Talavera-Mendoza, F., Rucano Paucar, F. H., Cayani Caceres, K. S., & Machaca Viza, R. (2023). Science and inquiry-based teaching and learning: a systematic review. *Frontiers in Education*,
- Valentine, J. C., & Cooper, H. (2003). Effect size substantive interpretation guidelines: Issues in the interpretation of effect sizes. *Washington, DC: What Works Clearinghouse*, 1-7.
- van der Weijden, F. A., van den Boer, M., Zijlstra, B. J. H., & de Jong, P. F. (2024). Implementation Takes Time: Reduction of Literacy Problems in Schools Implementing an Early-Literacy Intervention. *Journal of research on educational effectiveness*, 1-33. <https://doi.org/10.1080/19345747.2024.2384365>
- Vygotskij, L. S. f. a., & John-Steiner, V. (1979). *Mind in society: The development of higher psychological processes*. Harvard University Press.
- Vygotskii, L. S., Cole, M., John-Steiner, V., Scribner, S., & Souberman, E. (1978). *Mind in society: the development of higher psychological processes*. Harvard University Press.
- Vygotsky, L. S. (1978). *Mind in society: The development of higher psychological processes* (Vol. 86). Harvard university press.
- Wang, S. (2017). Understanding of 2017 Chinese STEM education white paper. *Modern Education*. (4-7)
- Wilson, C. E. (2020). The effects of inquiry-based learning and student achievement in the science classroom.
- Xi, x., & Xin, Z. (2023). *The 14th Compilation of Educational and Scientific Research Achievements in Huangpu District, Shanghai*.
- Xiang, Y., Liu, D., Liu, L., Liu, I. C., Wu, L., & Fan, H. (2025). Impact of case-based learning on critical thinking dispositions in Chinese nursing education: a systematic review and meta-analysis. *Frontiers in medicine*, 12, 1452051. <https://doi.org/10.3389/fmed.2025.1452051>
- Yakman, G. (2006). STEM pedagogical commons for contextual learning. *Unpublished class paper for EDCI*, 5774.
- Yang, Y.-T. C., Newby, T. J., & Bill, R. L. (2005). Using Socratic questioning to promote critical thinking skills through asynchronous discussion forums in distance learning environments. *The american journal of distance education*, 19(3), 163-181.
- Yata, C., Ohtani, T., & Isobe, M. (2020). Conceptual framework of STEM based on Japanese subject principles. *International Journal of STEM Education*, 7(1), 12.

- Ye, H. (2003). *Critical Thinking Test–Level I (CTT-LI)*. Guangzhou: Guangdong Education Press.
- Zhang, Q. (2008). *Historical Transitions and Implications of Science Education Reform in Post-War America*. H. R. H. Education.
- Zhang, W., & Hou, z. (2019). The realistic dilemmas and breakthrough paths of localized STEAM education implementation in China. *Global Education Review*, 48(10), 86-97.
- Zhou, Z., Kahana, M. J., & Schapiro, A. C. (2024). A unifying account of replay as context-driven memory reactivation. In (pp. 508): NewsRX LLC.
- Zhuo, X. (2019). *Using STEM course to cultivate students' critical thinking-take G attached middle school as example* (Publication Number 78) Guangxi Normal University]. China Academic Journal Electronic Publishing House.

Appendix

Interviews Forms

Interview Questions for Students:
1. How engaged were you in this lesson (1-10) 1 is less interest
2. How much interest do you have in this topic. (1-10)
3. What did you enjoy the most in STEAM education?
4. What did you not enjoy the most in STEM/STEAM education?

Interview Questions for Teachers	Aims
1. How important do you think the CT skills for students in this topic?	1. Teachers' attitude on critical thinking.
2. Can you share an example when students using critical thinking?	2. Are students have choice to practice critical thinking?
3a. What is your experience of using 7E IBL model?	3a. Teachers' feelings about 7E inquiry-based learning teaching methods.
3b. Did you find it is the easy to use, have you found any difficulties?	3b. The most difficult aspect when teachers adopting 7E IBL.
4. Do you have any suggestions?	4. What can be improved?
5. This model is for CT skills, what other aspect do you think it helps for your students?	5. Teachers' expectations on 7E IBL in STEAM education.

Class Observation Form

Instructor:

Class number:

Course topic:

Date and Time:

0: Disagree

1: Partly disagree

2: Maybe

3: Partly agree

4:

Agree

	Review Section	Number	Comment	Time duration
*Elicit	Study in groups			
	The link between prior and new knowledge			
	There are open questions from teachers			
	Clear learning objective for students			

	Review Section	Number	Comment	Time duration
Engage	Open questions from students			
	Real-life situation			
	Students can decide what to do through discuss with group members			
	There is interaction between teachers and students when decide what to inquiry			
	Teachers review students' idea of what to inquiry			

	Review Section	Number	Comment	Time duration
Ask questions, hypothesise	The use of subject theories is clear			
	Open questions from students in groups			
	Students have changes to practice CTS (critical thinking skills) by offering hypotheses			

	Review Section	Number	Comment	Time duration
Plan and Conduct Investigation	Student led; plans are coming from students			
	Teachers provide support when students have questions			
	Teachers offering demonstrations, questions, and guidance.			
	Leaners are enabled to examine and accumulate			

	different ideas			
	CTS: there are changes to develop and foster learners' process skills and critical thinking			
	Interaction between group members			

	Review Section	Number	Comment	Time duration
Observe Collect Data	CTS: there are chances of practising students' ability to infer.			
	CTS: the ability to induce			
	CTS: the ability to deduct new findings			
	Group collaboration			

	Review Section	Number	Comment	Time duration
Analyse Data	CTS: the ability to analyse data			
	CTS: the ability to numerate data			
	Group collaborate			

	Review Section	Number	Comment	Time duration
Present Results	Students conclude answers with evidence to support their hypothesis or offer a new answer to their questions			
	CTS: chance of practising evaluation ability			
	Students present findings with group members			
	There are questions from group members or teachers after each presentation			
	CTS: chance of practising explanation skills for presenters by answering questions			
	Teachers could provide support			

	Review Section	Number	Comment	Time duration
Elaborate	Teachers provide a new situation for students to reuse new curriculum knowledge			
	The new situation is from real-life			
	Students could give a design and production process plan.			

	Students' new knowledge can be further extended.			
	CTS: use analysis and inference skills to discuss possible solutions.			
	CTS: use deduction and numeracy skills to deduce how executable the plan is and whether it works well			

	Review Section	Number	Comment	Time duration
Evaluate	Students can self-assess their learning			
	Students can summarise new findings well			
	Students can reflect on their new knowledge			
	Receiving teachers' feedback and peer review			
	Students can reflect explicitly on the inquiry process and hypothesis			

	Review Section	Number	Comment	Time duration
Extend	Allow students to practice transferring the new knowledge to a different scenario.			
	learners to engage and ask questions initiatively			
	The transfer of knowledge is a near transfer			
	Enough time and appropriate guidance from teachers			
	The best plan is interpreted and accompanied by an explanation			
	Reuse CTS: use analysis and inference skills to discuss possible solutions.			
	CTS: use deduction and numeracy skills to deduce how executable the plan is and whether it works well			

Number of questions raised from one group:

Student completion rate for each task:

Questionnaires for CT dispositions - Chinese version

請您在每個問題目編號后面填上與您的觀點相對於的數值分數，用時 20 分鐘，謝謝。

(非常贊同 6 分, 贊同 5 分, 基本贊同 4 分, 基本不贊同 3 分, 不贊同 2 分, 非常不贊同 1 分)

CTDI-CV 批判性思維傾向測試題目 (例子)

維度	題號	內容
一， 尋找真理	1	面對有爭議的論題，要從不同的見解中選擇其一，是極不容易的。
	2	對某件事如果有四個理由贊同，而只有一個理由反對，我會選擇贊同這件事。
	3	即使有證據與我的想法不符，我都會堅持我的想法。
	4	處理複雜的問題時，我感到驚惶失措。
	5	當我表達自己的意見時，要保持客觀是不可能的。
	6	我只會尋找一些支持我看法的事實，而不會去找一些反對我看法的事實。
	7	有很多問題我會害怕去尋找事實的真相。
	8	既然我知道怎樣作這決定，我便不會反復考慮其他的選擇。
	9	我們不知道應該用什麼標準來衡量絕大部分問題。
	10	個人的經驗是驗證真理的唯一標準。
二， 開放思想	1	瞭解別人對事物的想法，對我來說是重要的。
	2	我正嘗試少作主觀的判斷。
	3	研究外國人的想法是很有意義的。
	4	當面對困難時，要考慮事件所有的可能性，這對我來說是不可能做到的。
	5	在小組討論時，若某人的見解被其他人認為是錯誤的，他便沒有權利去表達意見。
	6	外國人應該學習我們的文化，而不是要我們去瞭解他們的文化。
	7	不應該強逼我去為自己的意見作辯護。
	8	對不同的世界觀（例如：進化論、有神論）持開放態度，並不是那麼重要。
	9	各人有權利發表他們的意見，但我不會理會他們。
	10	我不會懷疑眾人都認為是理所當然的事。

Questionnaires for CT dispositions - English version

CTDI-CV Critical Thinking Disposition Test Questions

(Example questions)

Dimension	Question number	Content
1. Searching for the truth	1	I find is difficult to choose one side to a controversial topic.
	2	If there are four reasons for being in favour of something and only one reason for being against it, I will choose to be in favor of it.
	3	I stick to my ideas even when the evidence contradicts them.
	4	I'm looking for facts to support my beliefs, not facts against them.
	5	There are questions that I would be afraid to seek out the truth.
	6	Once I have made this decision, I don't think twice about other options.
	7	Personal experience is the only way to understand the truth.
	8	When faced with an important decision, I will try my best to collect all relevant information.
	9	The truth is nothing but personal opinions.
2, open minded	1	Knowing what other people think about things is important to me.
	2	I try to consider the opinions of everyone
	3	When faced with difficulties, it is impossible for me to consider all possibilities of events.
	4	In a group discussion, if someone's opinion is considered wrong by others, he has no right to express his opinion.
	5	Foreigners should learn our culture, not ask us to understand their culture.
	6	No one should ask me to define my opinion
	7	Being open to different worldviews (e.g. life, death, religions) is not that important.
	8	I ignore others' opinions
	9	If many people have the same opinion, then I will agree it.

Teacher training workshop PowerPoint slides (part of) examples



Project Title: An intervention study on implanting Inquiry-Based Learning (IBL) teaching method in secondary school STEAM education.

Objective: Increasing students' critical thinking skills.

Project Introduction: (your students will be in the experimental)

	February 2023	July 2023
Experimental Group (S2 and S3, aged 13-15, n=45)	Pre-test	Post-test
Control Group (S2 and S3, aged 13-15, n=45)	Pre-test	Post-test

Intervention Plan Timeline and Operating Process

Workshops IBL with 7E Learning Cycle (LC) Model

Lesson designs - co-design based on a theoretical framework (Before February 2023)

↓ once a week

Classes observation

↓ after every class

Collecting Feedback from teachers and students

end of each class, interview

Teachers' feelings and reflections: the advantages and disadvantages; the complexities when teaching; any suggestions

Students' fulfilment and interest: How would you like to study?

↓

Improvement

↓ once a month (from April - July 2023)

Adjust the teaching activities

Online seminars for all the STEAM teachers: Learning from others

Discuss any improvement required on the next teaching activities

尽管CTS很复杂，但通过时间和精力可以发展它 (Elker & Post, 2004)。

这是因为Elker和Post (2006) 认为CTS是通过“能力建设”的过程发展的。

同时，练习和重复对于发展对能力的掌握和帮助学生内化这些能力是至关重要的，从而使它们成为一个人思维过程的有机组成部分。

Dewey (1910) 和Scriven (2006) 也指出，一个人发展的推理技能和心理习惯越多，批判性思维就越强，包括识别、分析和评估论点等批判性思维的目标。这是由于实践发展了批判性思维所需的心理技能。

另一方面，桑代克 (1913) 的学习理论指出，刺激和反应之间的联系导致了学习。它的主要定律之一是运动定律，即连续而有练习的增加，而在停止练习时会减弱。当一个答案在实践中就正确地重复时，它可以帮助那些已经建立了一些联系的学习者巩固这些联系。

桑代克还强调了练习过程中反馈的价值，他认为死记硬背并不能促进学习，告诉学生他们的练习是正确的还是糟糕的，可以鼓励他们在不断练习中改善他们所学的东西 (桑代克, 1913)。

因此，对于STEAM教育的指导者来说，无论是对学生建构新的知识，还是提高他们的思维能力，在练习中注意所需的重复都是至关重要的。

Summary

Intervention classes with 7E IBL	Classes with normal method
2C & 2B	2A & 2D
3C & 3D	3E & 3B

5 Points when using 7E IBL theoretical framework

- 1 小組學習 Study in small groups
- 2 學生在小組中展示本節課的作品，並接受同學或老師的提問
Students will present results with group members in each class after inquiry (5-8mins)
- 3 老師提出一個或多個近轉移的問題，讓學生重複使用所學知識點
Elaborate: Teachers will ask a near transfer question to the whole class and students make a plan in groups (5-8 mins) there, students make plan without conduct it)
a) 老師對知識點提出一個問題 (near transfer) 的環節，學生實踐操作並解決這個問題。
b) 如這節課還有剩下的重要知識點，老師只需提出near transfer的問題，學生設計一個計畫，不需要動手操作。
- 4 學生自己知識點總結與討論 Evaluate: Teachers summary the new knowledge learned (2-3mins)
- 5 學生提出相似的問題，並討論給出解決方案
Extend: Students ask a near transfer question themselves and make a plan in groups (5-8mins)

Coding for interviews - examples

Blue: experimental group

Notebook

Green: control group

Teachers

7E IBL

Model

Questions **Highlight**

summaries or reasons of teacher's response

Example 1:

Interviewer: Over the entire semester, how would you evaluate the overall performance of the students in the two groups? Could you provide an assessment of the students in each group from various aspects?

Interviewee: 我觉得，实验班，用了你方法的那一些学生整体表现是比较好的。这个是比较明显的，他们是比较 focus on lesson 的。还有，问题他们都会自己做的比较多，就是不是太过问太多普通的问题。但是对照组的学生，一般我讲述一遍一个知识点以后，大部分对照组的学生是没听懂的，然后在操作环节或者下一节课还会不停的去问关于这个知识点或者软件操作的问题。不过在试验班的同学，我会在讲述问知识点以后，不停的问学生问题，不停的重复那些知识。因为我们 Steam 教育课程是每隔大概两周的时间，才会有一节课。所以如果我不是不停重复的话，他们很快就忘记了所有东西，就是实验组的同学这方面会比较好一些，他们都会记住最基本的一些 technics，我觉得这方面是挺明显的。还有就是实验组同学会比较 focus on the lesson。所以整体来说是实验组的同学是表现比较好的。但是他们最后的 products 有没有比较好的话，我觉得是没有对照组好很多，最后的 product。但是课堂上的表现明显是比较好。

Interviewee: I think the students in the experimental group, those using your methods, generally performed better. This is quite noticeable. They were more focused on the lessons and tended to solve problems on their own, without asking too many basic questions. On the other hand, most students in the control group didn't fully understand the material after I explained a topic once. During practical sessions or in the following classes, they kept asking questions about the same concept or how to operate the software. For the experimental group, after explaining a concept, I constantly ask students questions and repeat the material. Since our STEAM classes only meet once every two weeks, if I don't repeat things frequently, they would quickly forget everything. The students in the experimental group tend to retain the basic techniques better, which is quite noticeable. They are also more focused on the lesson. So overall, the experimental group performed better in class. However, in terms of the final products, I don't think there was a huge difference—perhaps not significantly better than the control group's products. But their in-class performance was definitely stronger.

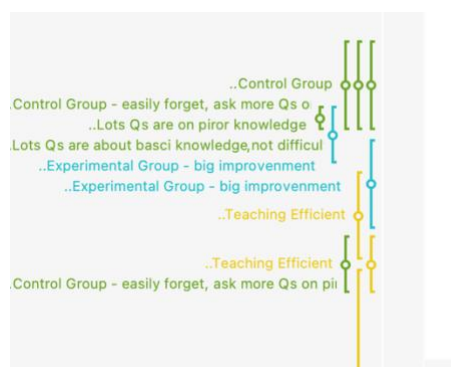


的，他们是比较 focus on lesson 的。还有，问题他们都会自己做的比较多，就是不是太过问太多普通的问题。但是对照组的学生，一般我讲述一遍一个知识点以后，大部分对照组的学生是没听懂的，然后在操作环节或者下一节课还会不停的去问关于这个知识点或者软件操作的问题。不过在试验班的同学，我会在讲述问知识点以后，不停的问学生问题，不停的重复那些知识。因为我们 Steam 教育课程是每隔大概两周的时间，才会有一节课。所以如果我不是不停重复的话，他们很快就忘记了所有东西，就是实验组的同学这方面会比较好一些，他们都会记住最基本的一些 technics，我觉得这方面是挺明显的。还有就是实验组同学会比较 focus on the lesson。所以整体来说是实验组的同学是表现比较好的。但是他们最后的 products 有没有比较好的话，我觉得是没有比实验组好很多，最后的 product。但是课堂上的表现明显是比较好。

Example 2:

Interviewee: 因为我们 steam 教育课程就是 problem base 的，我们教的东西是很少的。但是我们是隔两周多 才有新的课。所以比如我今天教了一些东西，然后可能是大半个月，才有另一节 Steam 课堂，所以对照组的班级学生他们已经完全忘记了，我上一节课说了什么，就像每一个人都在问问题，问一些很基本的之前学过的知识点或技术上的问题。就是说有关非常简单的基本知识点的问题。但是实验组的同学掌握 technics 比较好。就算是大半个月才有下一节课，并且至少他们还有 notebook。学生们就会记住他们学了什么。还有就是因为 在不停的重复知识点，他们对 basic 的 technics 会掌握的比较好。那么我在下一节课就可以教他们 focus 新的知识，继续 design 他们的 product 。就不是像控制组的班级一样，不停教他们之前学过的，最基本的技能怎么做。就是对照组的同学最基本的技能，他们都掌握不到。不过实验组的同学就会很快的继续做自己的 product 。所以我认为这对老师是比较好的，比较轻松。

Interviewee: Since our STEAM education curriculum is problem-based, we teach very little content. We also have a new class every two weeks or so. For example, if I teach something today, the next STEAM class might be in a month, so by then, students in the control group have completely forgotten what I taught them. It's like everyone starts asking questions about very basic, previously covered knowledge or technical issues—simple, fundamental things. However, the students in the experimental group grasp the techniques better. Even though the next class might be weeks later, at least they have their notebooks, and they can remember what they've learned. Because I constantly repeat the key concepts, they master the basic techniques well. When the next lesson comes, I can focus on teaching them new knowledge, helping them continue to design their products, rather than spending time re-teaching them the basic skills that the control group still hasn't fully grasped. The students in the experimental group quickly continue working on their own products. So, for the teacher, it's definitely easier and more relaxed.

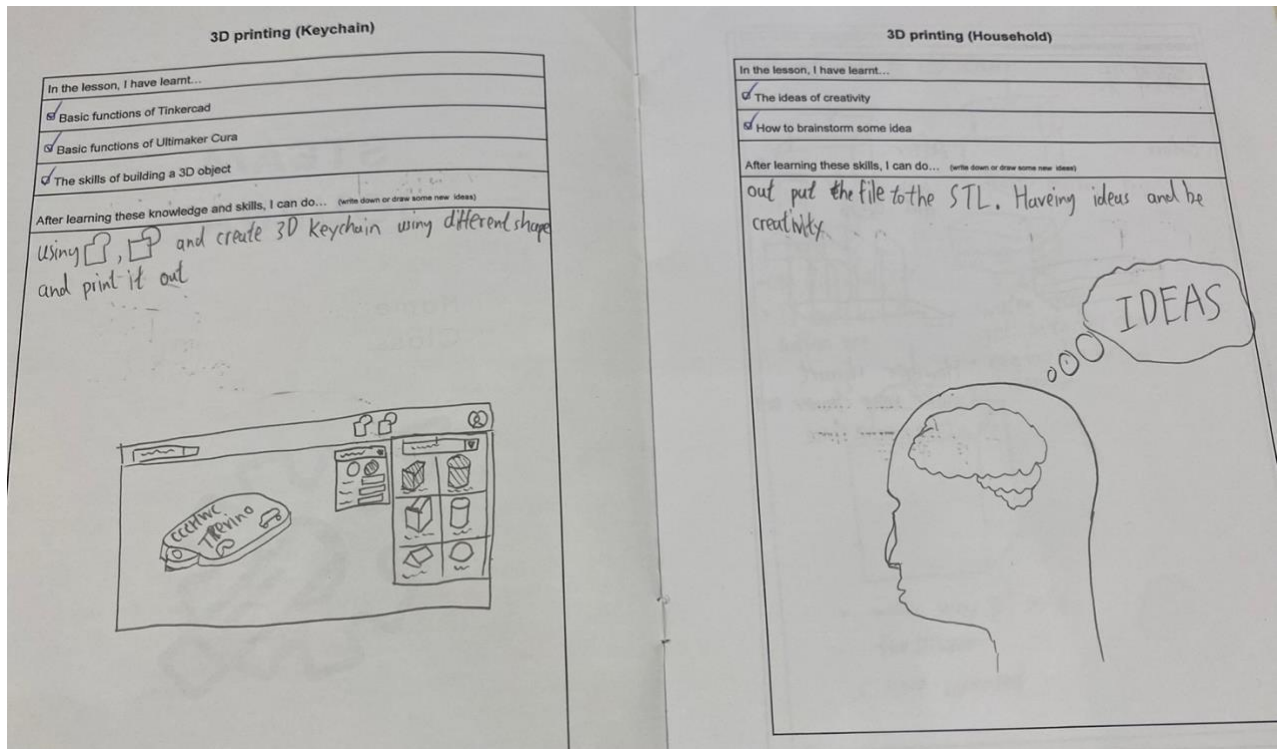


我们是隔两周多 才有新的课。所以比如我今天教了一些东西，然后可能是大半个月，才有另一节 Steam 课堂，所以对照组的班级学生他们已经完全忘记了，我上一节课说了什么，就像每一个人都在问问题，问一些很基本的之前学过的知识点或技术上的问题。就是说有关非常简单的基本知识点的问题。但是实验组的同学掌握 technics 比较好。就算是大半个月才有下一节课，并且至少他们还有 notebook。学生们就会记住他们学了什么。还有就是因为 在不停的重复知识点，他们对 basic 的 technics 会掌握的比较好。那么我在下一节课就可以教他们 focus 新的知识，继续 design 他们的 product 。就不是像控制组的班级一样，不停教他们之前学过的，最基本的技能怎么做。就是对照组的同学最基本的技能，他们都掌握不到。不过实验组的同学就会很快的继续做自己的 product 。所以我认为这对老师是比较好的，比较轻松。

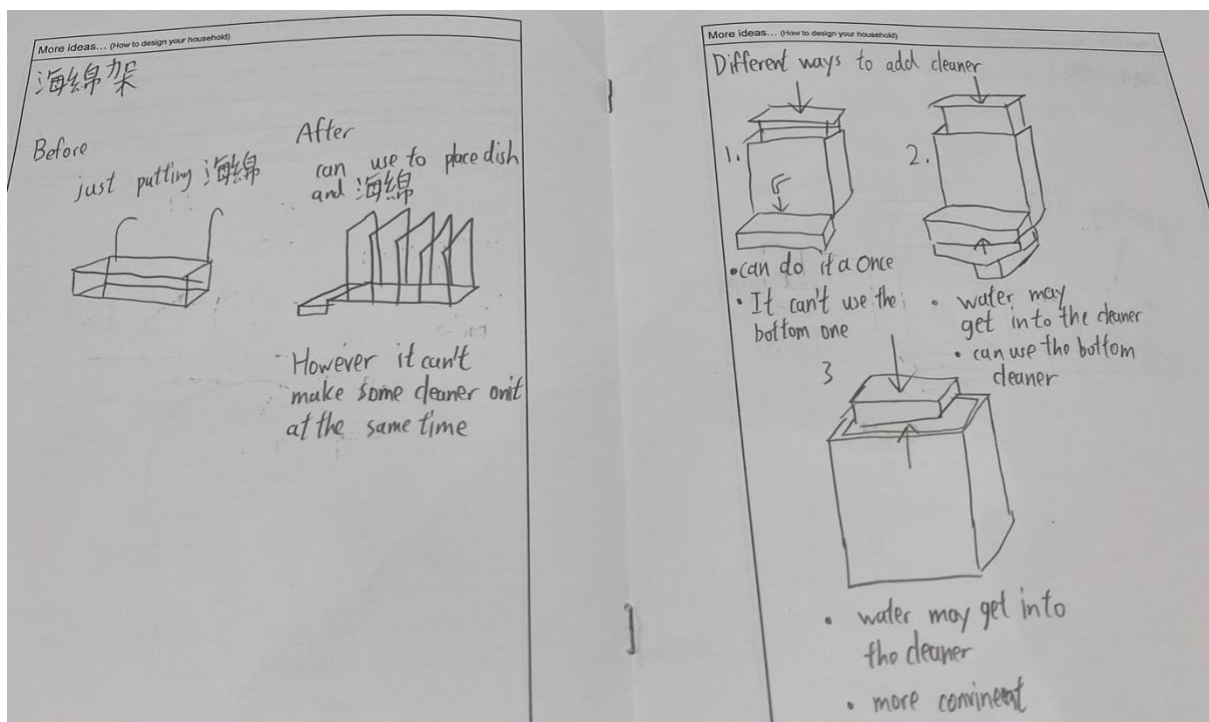
Notebook answers - examples

Example 1:

Page 1



Page 2



Page 3

More ideas... (How to design your household)

Last idea:

Reflection

I've learnt a lot for this topic, for example

- How to create things by using thinkercat
- How to output the design
- How to print things
- The concept of 3D printing
- How to think some ideas
- ect.....

Example 2:

3D printing (Household)

In the lesson, I have learnt...

The ideas of creativity

How to brainstorm some idea

After learning these skills, I can do... (write down or draw some new ideas)

Tooth holder

teeth holds toothbrush in place

bottom view

BRUSH YOUR TEETH

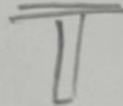
holes underneath to create a water seal also to let water leave the bottom of the shark

and ridges at the bottom for extra friction

The otter tooth brush holden
toothpaste
cover up



tooth paste
dispanser



ridges inside
mouth for
better placement

Students' products examples





