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Analysing a Chemistry Lesson on Ionic Bonding: Insights from a Learning Study

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Abstract

The aim of this paper is to report the insights gained from analysing an online Chemistry lesson on ionic bonding as part of a learning study conducted during the COVID-19 pandemic in 2021. The lesson was collaboratively developed by a group of seven high school Science teachers supported by two facilitators. Data collected includes the lesson plan, the transcript from the virtual lesson, and teacher reports. Insights were drawn from each phase of the learning study cycle – Study, Plan, Teach, Reflect. In the Study phase, the teachers came up with several presumed critical aspects based on responses to a two-part pre-test. In the Planning phase, a pattern of variation was used. In the online Teaching phase, we found potential critical aspects emerged when the students interacted with the object of learning, but this was not picked up by the teacher. The critical aspects identified from the learners' point of view include the number of shells for each atom and the number of electrons in each shell. In the Reflect phase, we consider the role of facilitators in guiding the lesson to focus on the discernment of critical aspects. The insights gained can potentially support teachers on how to plan and analyse lessons using the variation theory of learning, particularly in the context of online teaching.

Keywords: Chemistry; Ionic Bonding; Lesson Study; Research Lesson; Variation Theory; Online Teaching

Introduction

This paper reports on insights gained from analysing an online Chemistry lesson on ionic bonding as part of a learning study conducted during the COVID-19 pandemic in 2021. Ionic bonding was identified by the teacher group as one of the top three most difficult topics to teach and learn in Chemistry. Chemistry is one of three components in the Combined Science subject (subject code 5129), alongside Biology and Physics. Combined Science is studied by all Brunei senior secondary students who do not qualify for the pure science stream. These students sit for the externally assessed Ordinary Level examination in Year 11, at the age of 16-17 years.

Learning Study is derived from Lesson Study, a form of collaborative, practice-based professional learning that originated in Japan, that consists of cycles of experimentation and reflection on classroom instruction (Lewis *et al*, 2022). Like Lesson Study, Learning Study follows the "Study-Plan-Teach-Reflect" process, but with a key difference: it incorporates an explicit theory of learning in the design of teaching. According to Wood and Sithamparam (2021), being explicit about theory retains the potential to transform teacher education and professional development. In a learning study, the focus is on an object of learning, defined by Marton and Pang (2006) in their seminal work as a specific insight or skill that teachers wish to develop in students over a period or sequence of periods. The object of learning has two aspects: the direct and indirect objects of learning. The direct object of learning refers to the content while the indirect object of learning refers to the capability of using that content.

In analysing teaching and learning, it is important to differentiate between the intended, enacted, and lived objects of learning. The intended object of learning refers to what is planned, as outlined in the lesson plan. The plan details the sequence of activities designed to help students discern the critical aspects of the object of learning, which are typically identified through carefully crafted pre-tests or interviews. The enacted object of learning refers to what students can potentially learn in the classroom through the pattern of variation and invariance that was constituted jointly by both the teacher and the students. In other words, what varies and what remains constant in the lesson both constrains and enables learning. The lived object of learning refers to what is learnt. For example, what students learn depends on what aspects they discern and what dimensions of variation are made explicit during the teaching.

In addition to the concept of the object of learning, the concept of critical aspects is also synonymous with learning study and variation theory. Pang and Ki (2016) argue that critical aspects are not necessarily the things that students most often get wrong, overlook or forget. They assert that critical aspects should be defined from the learner's alternative ways of experiencing the object of learning and not necessarily based on the subject discipline or curriculum. Thorsten and Tvarana (2023) identified five different conceptions of critical aspects in their study. The highest conception is one in which critical aspects are seen as focal points for teaching the object of learning. They focus on what students need to discern in order to experience the object of learning in a certain way. The critical aspects are discerned as a specified description of the object of learning that can be the base for teaching it.

As facilitators, we used the lesson study variant called the learning study (Marton and Pang, 2006) as the professional development approach to support the Combined Science teachers. In a learning study, teachers focus on an object of learning and use the variation theory of learning to plan and analyse lessons to enable students to discern critical aspects (Kullberg et al, 2024). Previous studies on the use of variation theory in Chemistry can be found in the works of Vikstrom et al (2013) where for example, in analysing enacted patterns of variation, a frequently asked question was: What was possible for the students to discern and learn, and what was not?

Bergqvist and Chang Rundgren (2017) reported a list of students' alternative conceptions of, and difficulties understanding chemical bonding. These include:

- the use of the octet rule,
- focus on electronic configurations,
- lack of explanations for why bonding occurs and failure to explain that chemical bonds are due to electrostatic forces.

Thus, this study seeks to explore and answer the following question: What insights are gained from the four phases of learning study: Study, Plan, Teach, Reflect?

Methodology

A learning study essentially conducts "Study-Plan-Teach-Reflect" focusing on an object of learning as the point of departure. The first cycle of the learning study, which is the focus of this paper, consists of five meetings and one research lesson as shown in Table 1.

Table 1. Schedule and tasks for the learning study

Session	Phase	Tasks
#1	Study	Introduction to the PD. Selecting a topic for study. Identify tentative object of learning. Setting the pre-test.
#2	Study	Diagnose students' learning difficulties. Confirm the object of learning and its critical aspects.
#3	Plan	Plan the research lesson.
#4	Plan	Plan the research lesson (continued)
School-based	Teach	Research lesson in school (online).
#5	Reflect	Evaluation of learning outcomes.

The participants in this study came from five different schools across Brunei Darussalam. Through our experience as facilitators, we observed that guiding teacher groups to focus on the object of learning and designing lessons around critical aspects can foster a rich environment for systematic teacher action research, such as Learning Study.

Data collected for this research included the collaboratively developed lesson plan and the transcription of the online research lesson, which was conducted via Microsoft Teams. The steps involved in our analysis were as follows:

1. Downloading the video of the lesson from Microsoft Teams.
2. Transcribing the lesson.
3. Preparing an analysis template, consisting of three columns: time during lesson, description of activity and analysis
4. Conducting independent analyses of the lesson and sharing these findings with one another.
5. Watching video of the lesson together, pausing at key points of the video to consider what we saw from the enactment.

These methods provided a comprehensive understanding of how the lesson was delivered and where critical aspects were addressed.

Results and Discussion

The Study Phase

In this phase we present the outcomes of the pre-test analysis and discuss the possible critical aspects of learning ionic bonding. The pre-test question is as follows:

The pre-test:

(a) Describe the formation of ionic bonds in NaCl and $MgCl_2$.

(b) Use cross and dot diagrams for the formation of ionic bonds in NaCl and $MgCl_2$.

Table 2 outlines suggested answers from the teachers' point of view. Note that these are in the terminology used by Thorsten and Tvarana (2023, p5) on "presumed critical aspects", based on teachers' disciplinary and curriculum knowledge as well as their knowledge and familiarity of content and students.

Table 2. Answer rubric for the pre-test question

Level	**(a) Describe the formation of ionic bonds in NaCl and $MgCl_2$.**	**(b) Use cross and dot diagrams for the formation of ionic bonds in NaCl and $MgCl_2$.**
1	Incorrect answer	Incorrect answer
2	Partially correct answer that states: 1) electron transfer from Na atom to Cl atom (for NaCl) and Mg atom to Cl atoms (for $MgCl_2$); 2) full 8 e^- in valence shell (stable); 3) NaCl: Na atom lost 1 e^- to form Na^+ ion while Cl atom gains 1 e^- to form Cl^- ion and $MgCl_2$: Mg atom lost 2 e^- to form Mg^{2+} ion while 2 Cl atoms gain 1 e^- each to form 2 Cl^- ions;	Partially correct answer that shows at least 3 out of 5 points listed below.
3	Fully correct answer that states ALL of these points: 1) ionic bonds formed between metal and non-metal; 2) electron transfer from Na atom to Cl atom (for NaCl) and Mg atom to Cl atoms (for $MgCl_2$); 3) full 8 e^- in valence shell (stable); 4) NaCl: Na atom lost 1 e^- to form Na^+ ion while Cl atom gains 1 e^- to form Cl^- ion and $MgCl_2$: Mg atom lost 2 e^- to form Mg^{2+} ion while 2 Cl atoms gain 1 e^- each to form 2 Cl^- ions; 5) strong force of attraction between the oppositely charged ions formed the ionic bond.	Fully correct answer that shows: 1) a dot is used to show e^- in one atom while a cross is used in the other atom; 2) correct number of e^- in the shells of both atoms; 3) correct electronic configurations before and after ionic bond is formed; 4) correct arrow(s) from metal to non-metal atoms; 5) square brackets drawn with correct numerical charges at top right of the bracket for ions.

There are three different levels of understanding for each part question, with level 1 as the lowest and level 3 as the highest. For part (a), five critical aspects related to ionic bonding were identified:

1) ionic bonds formed between metal and non-metal;
2) electron transfer;
3) full 8 electrons in valence shell;
4) loss and gain of electrons to form ions;
5) electrostatic force of attraction between oppositely charged ions.

For part (b), the five critical aspects are:

1) the proper use of dot and cross on atoms;
2) correct number of electrons in the shells of both atoms;
3) correct electronic configurations before and after ionic bonds is formed;
4) correct arrow(s) from metal to non-metal atoms;

square brackets with correct numerical charges.

The Plan Phase

The planning incorporated a sequence of patterns of variation, particularly in the ratio of metal to non-metal in ionic bonding. For example, lithium fluoride (LiF) forms when a lithium atom donates one electron to a fluorine atom, allowing lithium to achieve the electronic configuration of the noble gas helium. Similarly, calcium fluoride (CaF_2) is formed when calcium transfers two electrons to fluorine, resulting in calcium achieving the electronic configuration of the noble gas neon. In this design, the non-metal (fluorine) was kept constant,

The Task
Describe and draw the formation of ionic bonding for lithium fluoride (LiF), calcium fluoride (CaF_2) and an unknown compound X_2Y.

while the metal element was varied from lithium to calcium, in terms of the number of outermost electrons donated to fluorine. Prior to the first research lesson, the group decided to develop asynchronous learning materials that students could access and interact with at their own pace. These materials included two videos explaining ionic bonding and a collaborative task for students to complete with their peers.

During the research lesson, students were expected to present their answers, while the teacher's role was to probe gaps in the students' understanding and clarify any misconceptions.

The Teach Phase

Potential critical aspects not picked up by the teacher

In the research lesson the teacher covered four out of the five critical aspects of the object of learning ionic bonding formation. The aspect that was not covered was the electrostatic force of attraction between oppositely charged ions. Interestingly, a critical aspect that had not been anticipated emerged during the lesson, reflecting the dynamic nature of teaching, as described by Lo (2012): "Critical features cannot be uncovered in pre-lesson interviews (or pre-test) but only emerge when the students interact with the object of learning during the lesson" (p. 78).

Below is an extract from the lesson that illustrates the unfolding of this unexpected aspect.

Teacher: *"So how many electrons are there in lithium and fluorine? You can check this from your Periodic Table."*

Teacher typed the question on chat box in Teams: *"How many electrons are there in Li and F? How are they arranged in their shell?"*

Student: *"Lithium have 3 electrons. And fluorine there is 9 electrons. The electrons are arranged with 2 in the first shell and the rest 8 all above."*

Teacher: *"Ok just to clarify that it's actually for other shell it would be 8 electrons. Ok so how many electrons are there in lithium, the outer shell of lithium?"*

SILENCE

Teacher: *"How many electrons are there in the outer shell of lithium and how many in fluorine?"*

SILENCE

Student: *"Lithium have 2, 8, 3."*

Teacher: *"Yes, lithium has got 3 in total but how about the outermost shell?"*

Student: *"Only 2 electrons."*

Teacher: "Only 2?"

SILENCE

Student: *"1 only Teacher. 1."*

Teacher: *"Ok lithium has got 1 and fluorine has got?"*

Student: *"7"*

Teacher: *"7. Ok so in this case lithium will transfer one electron to fluorine."*

In this interaction, the student struggled with the correct electronic configuration. The student initially implied that lithium has three shells and incorrectly identified the configuration as 2, 8, 3 instead of the correct electronic configuration, 2, 1. This demonstrated a misunderstanding about how electrons are arranged in different shells and the concept that each shell can hold a certain number of electrons.

To clarify:

- **Lithium** has 3 electrons, with a configuration of **2, 1** (2 in the first shell, 1 in the second).

- **Fluorine** has 9 electrons, with a configuration of **2, 7** (2 in the first shell, 7 in the second).

This misunderstanding highlights a critical aspect that was not fully discerned: the number of shells for each atom, the number of electrons in each shell, the arrangement of electrons across different shells and the rule that shells must be filled sequentially. The general rule is that the innermost shell is filled first. This shell can contain a maximum of two electrons. The second shell can hold a maximum of eight electrons, and when this shell is filled, electrons will go into the third shell, which also holds a maximum of eight electrons. Then, the fourth shell begins to fill.

In another part of the discourse, the class was asked to predict the elements in the ionic compound X_2Y with atomic numbers of X and Y given as 11 and 8, respectively. A student incorrectly identified X as hydrogen because the diagram only showed one electron in the outer shell (Figure 1). Although the electronic configuration was written as 2, 8, 1, only one shell was shown. It is not clear if the student who wrote this is aware of the existence of three shells in X and that the electrons are placed from the inside out. The first two electrons are in the first shell, the next eight electrons are in the second shell and the last one electron is in the third shell, which is the outermost shell for X.

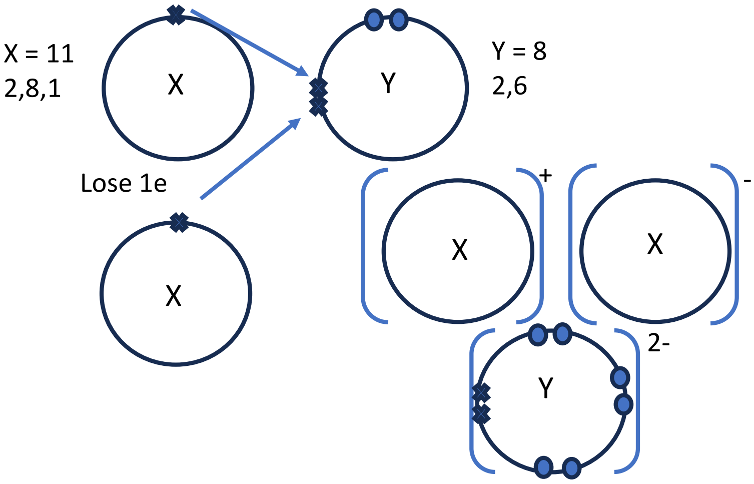

Figure 1. A group's drawing of an ionic bond formation (redrawn for clarity)

Below is the extract:

Teacher: *"Maybe you can have a guess on what is X and what is Y? On the Periodic Table."*

Student: *"Hydrogen, Teacher."*

Teacher: *"Hydrogen. Which one is hydrogen?"*

Student: *"X."*

Teacher: *"Hydrogen. Why do you think it is hydrogen?"*

Student: *"Because have only one electron."*

Teacher: *"Hmmm, if it is only 1 electron, it will be hydrogen. In this case, X has 11 electrons. So, it is stated in the question X has 11 electrons."*

At this point, another student correctly identified X as sodium and Y as oxygen. The teacher was satisfied with this correct response but missed the opportunity to address the confusion about X being hydrogen. It was only after a facilitator alerted the teacher that the teacher revisited the issue.

Teacher: *"Someone said X could be hydrogen just now. So, there might be some* *confusion here because if you look at the drawing here, there is only 1 electron on X. Ok, so you might think this is the hydrogen but what is happening here actually these two students are drawing only the valence shells. Ok so, this is the most outermost shell 2,8,1. The outermost shell has only 1 electron. But it doesn't mean that this atom has got 1 electron only. Ok? So, if you draw, everything, it will be three shells originally. It is my bad that I didn't tell you to draw full shells at first."*

The teacher made the number of electron shells for element X explicit, which was a critical aspect for students who had not yet discerned this concept. This clarification is essential because identifying an element cannot be based solely on just the number of electrons in its valence shell. Students must also discern the total number of electron shells for each atom. The students' drawings in Figure 1 further suggest that depicting only the valence shell may be insufficient. We tentatively conclude here that it is critical to draw the electron shells in full and show how the electrons are arranged when illustrating ionic bonding. Drawing only the valence shell or outermost shell can lead students to conclude the wrong identity of the element.

The role of the facilitators

Facilitators played a crucial role during the research lesson, offering guidance to the teacher via WhatsApp when potential gaps in student understanding emerged. During the research lesson, the facilitators prompted the teacher at least twice through WhatsApp to consider what the students were trying to say. In the previous instance, we shared one example of the facilitator prompting the teacher to explore why a student believed X to be hydrogen, leading to a valuable clarification on electronic configuration and shell arrangement.

In this second example, following a prompt from the facilitators, the teacher referred to a student's answer and asked:

"As we can see from your diagram, so what happen here is calcium, the electronic configuration is 2, 8, 8, 2 and you said from what I understand here, 2 of these electrons are transferred to fluorine. One each to each one, right? Why is the calcium transferring the electrons away? Why is Ca losing 2 electrons? Why is F gaining 1 electron?"

A student responded in the chat box. The teacher read out the answer.

"Fluorine becoming a full shell."

"Only 1 electron."

The student's answer was correct. The teacher then raised a question which was open to all students. It appeared to be a good question, a question of contrast, and it seemed to have been prompted by the discussion so far.

"Why does Li lose only 1 electron, but Ca loses 2 electrons?"

The teacher showed two groups' answers on the screen (Figure 2). This was not in the lesson plan but rather impromptu. It appeared to motivate some students to respond.

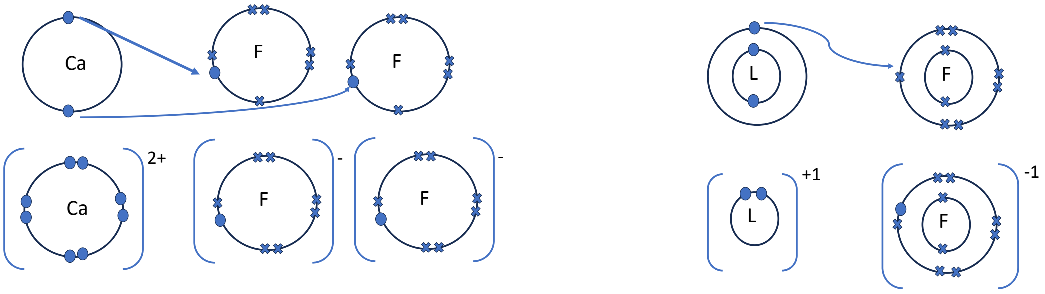

Figure 2. Two groups' drawings of ionic bond formation for CaF_2 and LiF

"So, one of you said just now said fluorine is gaining 1 electron to have full electron shell. Then what is the purpose of calcium and lithium losing electrons?" A student replied:

"Because lithium to make the shell full ... Lithium have 2, 1 electrons. That's why he lose one electron – to make the shell full."

The teacher asked:

"How about calcium?"

A student said:

"Calcium is 2, 8, 2 then he must lose 2 electrons to make the shell full."

Here the student's response was missing one part of the shell. However, losing 2 electrons is correct hence the teacher helped clarify the concept:

The teacher continued:

"Ok. That's good. Let me rephrase. Lithium as one of you has said has got the configuration of 2, 1 so it removes 1. Whereas calcium has 2, 8, 8, 2, it removes 2. Ok so when that happens, we say they have full shell so that's good."

This part of the lesson demonstrated the teacher's ability to foster deeper student understanding, driven by facilitators' interventions. Additionally, the use of students' diagrams to visualise the contrasting behaviours of lithium and calcium in ionic bonding was highly effective.

The Reflect Phase

The research team noted a significant challenge in student participation, as only four out of nineteen students attended the online lesson. Of those who attended, one student demonstrated a more advanced understanding of ionic bonding concepts. The teacher facilitating the lesson also reflected that the asynchronous part of the lesson did not work as well as intended. It appeared that students struggled in engaging with their peers to complete the asynchronous tasks assigned to them. They were also unfamiliar with engaging in peer discussions in an online environment. According to the teacher, the students may need more guidance on how to lead and participate in peer discussions.

More critically, the facilitators identified two new critical aspects of student learning during the lesson that had not been captured in the initial lesson design or reported in existing literature. The teachers' presumed critical aspects, while necessary, were insufficient to address the real gaps in student understanding. The critical aspects identified during the lesson include the number of electron shells for each atom and the arrangement of electrons within these shells. Through student dialogue, it became clear that focusing solely on the valence shell—the outermost shell of an atom—was misleading for some learners. Instead, drawing the full arrangement of electron shells proved vital for helping students accurately discern the structure of atoms involved in ionic bonding. These aspects are critical for these learners and may not be critical for other learners.

The facilitators also reflected on the value of learning from students' alternative conceptions. Identifying what students have not yet discerned is just as informative as understanding what they do know. In this case, alternative conceptions about atomic structure were not anticipated in the pre-lesson phase but became clear through student responses. These unanticipated critical aspects serve as powerful teaching moments, offering educators the opportunity to reshape their strategies in real time to better meet the students' needs.

Discussion

The learning study reported in this paper provides further evidence of the usefulness of the variation theory of learning to plan and analyse lessons (Kullberg et al, 2024). Through the lens of variation theory, the critical aspects of the object of learning were identified from the lesson transcript, focusing on the number of electrons in each shell and the number of shells for each atom.

These critical aspects, as far as we are aware, have not been previously reported in the literature, making them noteworthy discoveries from the learners' perspective in this study. They are students' alternative ways of experiencing the object of learning.

Pang and Ki (2016) argue alternative ways of experiencing the object of learning have to be considered and addressed during the teaching. The timely intervention by the facilitators during the lesson was crucial in enabling the teacher to recognise and address these alternative perspectives. This allowed for an in-the-moment adjustment of the teaching approach to better meet the students' needs. However, it is important to acknowledge that we do not have sufficient data to confirm whether the learners fully grasped the critical aspects at the end of the lesson. Facilitator interventions during a learning study are rarely reported in the literature. However, we argue that the purpose of a research lesson is to help learners discern the critical aspects and if these can be done during the lesson through a gentle nudge, it provides the opportunity for reflection-in-action (Schon, 1983).

In future studies, the findings from this lesson could inform a more systematic approach, particularly in teaching ionic bonding. For instance, showing the full electronic configuration of each element—not just the outer shell—could provide a clearer foundation for students to understand how bonds are formed. A more structured exploration of electron shells and their arrangement might address the alternative conceptions observed in this study, which students struggled to fully discern the nature of ionic bonding by focusing solely on valence electrons.

It is important to acknowledge the limitations of this study, particularly in relation to student participation during the COVID-19 pandemic. Only four out of nineteen students attended the lesson online, significantly reducing the sample size and, consequently, the breadth of data available for analysis. Additionally, the asynchronous learning activity did not work as effectively as intended. According to the teacher, this was largely due to students being unfamiliar with leading and participating in online discussions.

Conclusion

This study seeks to find out the insights gained from the four phases of a learning study on ionic bonding. In the Study phase, teachers initially identified presumed critical aspects based on their analysis of a two-part pre-test question. These aspects guided the lesson planning, but did not fully align with what students ultimately needed to discern. During the Planning phase, a pattern of variation was carefully designed to bring out these aspects. In the Teaching phase, potential critical aspects emerged as students engaged with the object of learning, but this was not picked up by the teacher. The critical aspects identified from the learners' point of view include the number of shells for each atom and the number of electrons in each shell—key concepts that the students struggled to grasp. In the Reflect phase, the role of facilitators in guiding the teacher to focus on the discernment of critical aspects was essential. The presumed critical aspects identified by teachers at the outset differed from those that arose from the learners' actual experiences. This discrepancy underscores the importance of addressing students' alternative conceptions during teaching and adapting instructional strategies accordingly. The study also emphasised the significance of facilitator interventions during the lesson. Facilitators provided timely nudges to help the teacher notice and address students' alternative conceptions, allowing for reflection-in-action. This approach is not commonly reported in research studies but proved to be a valuable part of the learning process here.

In conclusion, this learning study not only affirms the usefulness of variation theory in both lesson planning and analysis but also highlights the need for flexibility in teaching to accommodate learners' diverse perspectives. While challenges such as limited student attendance due to the COVID-19 pandemic affected the overall outcome, the findings suggest that future lessons could benefit from a more explicit focus on critical aspects like the full electronic configuration of atoms, rather than just the outer shell. By recognising and addressing students' alternative conceptions, teachers can enhance understanding and support deeper learning. Further research is needed to assess the long-term impact of such strategies and to refine approaches for both in-person and online learning environments.

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