

Development of POGIL-Style Classroom Activities for an Introductory Chemistry Course

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Abstract

Foundations of Chemistry IA (semester 1) and IB (semester 2) courses at the University of Adelaide are undertaken by Level I students pursuing a wide variety of degree programs that require a year of chemistry study. As a consequence, many students who have studied little, or no, chemistry in high school enrol in these courses. We redeveloped these courses for 2012 to cater to students with little or no chemistry background, with group-based Process-Oriented Guided Inquiry Learning (POGIL) style activities used to deliver the majority of the course content.

We have been developing POGIL-style activities for all topics within both courses, but particularly in the area of introductory organic chemistry, for which few activities currently exist. Three organic chemistry activities were developed and subsequently tested in workshops run in November 2011 and April 2012. Student volunteers completed a survey consisting of Likert and open-ended questions related to the activities at the conclusion of each workshop. A focus group was also held at the conclusion of the second workshop. Feedback from the workshops and focus groups helped to refine and further develop the activities by suggesting the reorganisation of some questions for a better flow and make them less text-heavy.

Introduction

The value of collaborative, small-group learning and peer-assisted teaching has been well-documented in the educational literature (for examples, see Boud, Cohen & Sampson, 1999; Bowen, 2000; Cooper, Cox, Namouz & Case, 2008; Falchikov, 2001). The incorporation of such student-centred approaches in teaching generally requires less of a focus on the traditional lecture format of content delivery, usually due to time constraints (Michaelson & Sweet, 2008). Ways of achieving a collaborative learning environment include Process Oriented Guided Inquiry Learning (POGIL) (Farrell, Moog & Spencer, 1999; Moog, 2009; <http://www.pogil.org>), Peer-Assisted Learning (Boud et al., 1999), Peer Instruction (Crouch & Mazur, 2001) and Team-Based Learning (Michaelson & Sweet, 2008). Students benefit from collaborative learning in a variety of ways, including development of problem-solving (Robblee, 1991) and critical thinking skills (Johnson & Johnson, 1989), while use of the method has reportedly resulted in fewer student misconceptions (Basili & Sanford, 1991).

POGIL emerged in college Chemistry courses in the United States in the 1990s, and has now been implemented by over 1000 teaching staff across the USA (<http://www.pogil.org>). Its philosophy is that students learn by doing, and that the lecturer acts more as a facilitator of learning rather than a transmitter of knowledge. What distinguishes POGIL from other

inquiry-based methods is that the level of guidance is directed towards concept acquisition, a vital feature for students with little or no prior knowledge of chemistry. A POGIL activity comprises three main parts: Model, Data and/or Information; Critical Thinking Questions (CTQs) and Applications (Farrell, Moog, & Spencer., 1999). The activity begins by providing students with some background on the topic, in the form of a paragraph or two of text, a diagram or a table, followed by guided inquiry questions that allow students to make connections and draw their own conclusions, enabling them to reach answers on their own rather than having someone inform them that 'this is so'. The activity concludes with application questions that provide further practice in using the concepts covered by the CTQs, and are designed to be completed by students as homework outside of class time. Workbooks containing such POGIL exercises have been published (Garoutte, 2007; Hanson, 2007; Moog & Farrell, 2011).

Farrell et al. (1999) report that a true POGIL classroom involves students working for the entire class time on activities through discussion in small groups of between three and five individuals, with each student in the group assigned a specific role. Roles include Presenter (provides answers to the class on request from the instructor), Reflector (analyses group dynamics to see if work can be done more efficiently/harmoniously), Manager (in charge of the group and ensures members are acting according to their roles) and Recorder (records the names of group members and any important points arising from discussion of activities). Not all of these roles may be used, and other roles may be assigned, depending on the group size.

Case Study

Level I Foundations of Chemistry IA (semester 1) and IB (semester 2) courses at the University of Adelaide are undertaken by students from extremely diverse academic backgrounds enrolled in degree programs both within and outside of the Faculty of Sciences. Many of these students are enrolled in a program that requires a year of chemistry at level I, such as Animal Science, Viticulture & Oenology, and Health Science. This means that many students who have never studied chemistry in high school enrol in these courses, which can have up to 400 students enrolled per semester. Prior to 2012, neither Foundations of Chemistry IA nor Foundations of Chemistry IB had SACE Stage 2 (Year 12) Chemistry as a prerequisite, but assumed much of this knowledge, resulting in students who had never studied chemistry before (i.e. no Year 11 or 12 knowledge) having to come to terms with unfamiliar course content very quickly. While some students thrived in this situation, others found it more difficult. For the latter group of students, the study of chemistry can therefore be a roadblock preventing their progress through their chosen degree program.

The Discipline of Chemistry recognised that in the years to come, an increasing mixture of students who have not studied chemistry at secondary school will be enrolling in degree programs that require a year of chemistry study. The Discipline wished to maximise learning opportunities for these students by revising not only the content of the Foundations of Chemistry courses, but also the method by which they are taught.

After a discussion among Chemistry academic staff to weigh up the various benefits of different styles of collaborative learning, we came to the conclusion that the style of learning offered by the POGIL format was a good fit for our students, especially given that it seemed to be more adaptable to changing circumstances than other approaches. In addition, prior experience within the Discipline had exposed us to POGIL, with some Chemistry academic staff previously attending workshops and presentations showcasing this method of teaching.

Intervention

Course content for the new Foundations of Chemistry IA and IB has been redeveloped to begin at an introductory level, rather than assuming any prior Chemistry knowledge. Each semester-long course consists of four modules, with group-based POGIL-style activities used to deliver the majority of the course content during allocated lecture time, supported by separate weekly tutorial sessions, in which practice problems are discussed. Regular assessment through online tasks and short in-class tests provides students with continual feedback to guide and monitor their progress. It was anticipated that these group learning sessions would give students more of an opportunity to actively engage with the course content than the previous, more traditional, format. The course content needed to be significantly revised, and in most cases completely rewritten, to accommodate the restructure of these courses, including the incorporation of group-based learning activities.

The restructure meant that some course content had to be dropped to allow time for activity-based learning. Chemistry staff consulted with those from other disciplines within the University to seek their opinion on which chemistry topics they would most like covered in first year. These preferences were taken into account when structuring the new Foundations of Chemistry courses so that the combination of Foundations of Chemistry IA and IB provides students with a good basis of chemistry knowledge that will enable them to continue their studies in level II courses not offered by the Discipline of Chemistry, but which may have first year chemistry as a prerequisite. For students studying the Foundations pathway who wish to continue with level II chemistry, we have created a summer semester course that allows them to take a three-semester pathway into level II chemistry, in contrast to the two-semester pathway offered by the flagship first year courses, Chemistry IA and IB.

This project arose from the restructure process, with the more specific aim of developing POGIL-style activities in the area of introductory organic chemistry, with their construction guided by feedback from current chemistry students. To date, the majority of POGIL teaching efforts worldwide have been concentrated on the area of general chemistry (Doymus, 2007; Lewis & Lewis, 2005; Lyon & Lagowski, 2008), although other studies, such as the one by Hein (2012), show that POGIL is very effective in assisting students in learning organic chemistry concepts. However, very few POGIL activities exist for introductory organic chemistry. Much of what is already available is for second year-level college courses in the US (for example, Straumanis & Simons (2008) and Perry & Wight (2008)) and hence is aimed at too high a level for this course. Therefore, we wished to develop activities to cover subtopics such as functional groups and physical properties of organic compounds for use in the organic chemistry section in the semester 2 Foundations of Chemistry course.

Development of activities

Development of three organic chemistry POGIL-style activities began in late 2011, with a view to creating content that could be incorporated into lectures providing a balance between lecturer presentation and time spent on activities. The activities produced covered the topics of proteins, physical properties of alkanes and introduction to alkenes and alkynes.

The development of these activities followed the reported POGIL activity structure of providing students with some information on the topic to be covered, followed by a series of critical thinking questions. The Application section was not included in any of the activities, as the course structure was such that they were intended to be supported by weekly tutorial sessions in which discussion of practice problems (provided separately) would be undertaken.

The information provided gives students a start on the topic, but intentionally leaves room for them to make inferences and connections to build up the complete picture on their own, using the CTQs as a guide.

The activities were developed using a two-cycle iterative process of workshops in 2011 and 2012 (described in the Data Collection section that follows) to gain feedback on their content and structure from Chemistry students at both undergraduate and postgraduate levels. The students who attended the workshop sessions provided valuable feedback that gave us an insight into their thoughts about inquiry-based learning and also greatly assisted with refining the activities before their implementation. This feedback was especially useful in the development of the “proteins” activity: initially, this activity featured a very text-heavy ‘Information’ section, providing students with almost a full page of fairly dense text that needed to be read before they could even begin to work their way through the questions that followed. Attendees in the November 2011 workshop found this to be rather off-putting, and suggested that the activity be made “less wordy”. This advice was taken and the information at the start of the proteins activity was reduced from almost a full page of text to just less than half a page.

Other changes were made based on feedback from the workshops included rewording of certain questions for purposes of clarity and changing the order of some questions within the activities in order to improve the flow. Accordingly, the activities were further refined in preparation for their implementation into the semester 2 Foundations of Chemistry course in July/August 2012. The final version of each of the three activities is provided in Appendices 1-3.

Data Collection

Trial lecture

Prior to the implementation of this project, the Chemistry discipline ran a 2-hour trial lecture/workshop in August 2011 with current Foundations of Chemistry students to gauge their response to the restructure of lectures and the implementation of POGIL activities in general. Twenty-three students attended this workshop and were provided with a copy of some of the revised material and accompanying activities. Workshop participants were given the background to the proposed restructure, and the process of a POGIL classroom was explained. The trial lecture containing POGIL-style content, covering the topic of equilibrium, was presented by the same staff member who had taught the same material using a traditional lecture format to students earlier in the semester. At the end of the trial lecture, students were asked to complete a survey form containing Likert and open-ended response questions in order to provide feedback. The survey contained the following Likert response statements:

- The lecture stimulated my enthusiasm for further learning.
- In the lecture, I felt part of a group committed to learning.
- It was made clear what was expected of me.
- Working on activities in a group during the lecture was useful for my learning.
- The lecture format motivated me to learn.
- The lecture helped me to develop my thinking skills (e.g. problem solving).
- I understand the concepts presented in this lecture.
- The way this lecture was presented is better than the current format used for Foundations of Chemistry lectures.

Workshops

A small-scale trial with first year students who had just completed Foundations of Chemistry studies was conducted using the newly-developed organic chemistry activities in November, 2011. Students were introduced to the three developed activities, the rationale behind their introduction and implementation and the concept of a POGIL classroom, and were then asked to complete the activities in the same way as a student would in class. At the end of the session, participants were asked to complete a survey, featuring open-ended questions as well as their responses to the following Likert-style statements:

- The activities stimulated my interest in organic chemistry.
- It was clear to me what to do in the activities.
- The activities helped me to develop my thinking skills (e.g. problem-solving).
- I understand the concepts presented in these activities.
- Completing these activities has given me more confidence in approaching assessment tasks in organic chemistry.

The activities were updated based on feedback from the November workshop and the new versions trialled in April 2012 in a workshop session featuring a mixture of second year undergraduate and postgraduate chemistry students. The input of second year undergraduate chemistry students was sought because first year students studying Foundations of Chemistry in 2012 would be seeing the activities that were to be trialled in lectures later in the year. In addition, it was thought that the greater level of experience of second year students could provide a useful viewpoint compared to the first year students consulted in the November workshop. The postgraduate students included in this workshop were employed as casual demonstrators for Foundations of Chemistry practicals, and it was considered that their feedback could be particularly useful, given that they work closely with the target cohort, and have valuable insights into the ways these students learn and the potential difficulties they face. The structure of this workshop was the same as that held in November. A paper survey similar to the one used in the November workshop was provided to participants, who were asked to complete it to give their feedback on the activities. The Likert statements posed in the April survey included the first four statements used in the November survey, with two additional statements: 'There was a strong inquiry focus to the activities' and 'The activities helped me better understand chemistry'. Four open-ended questions were also included:

- Overall, what were the best aspects of the activities, and why?
- Which of the activities did you think was the best, and why?
- Did you find the wording of the questions and the structure of the activities appropriate? If not, please let us know how they could be changed to improve the activities.
- The activities could be changed in the following ways to improve my learning.

Focus group

At the conclusion of the April workshop, a focus group was run to enable more time for conversation and general feedback. Students engaged in conversation with a facilitator (who was uninvolved in the development of the activities), who recorded and then transcribed the resulting discussion.

Analysis of Data

Results from the trial lecture

The response to the trial lecture was extremely positive (Table 1). The first year students who participated favoured the introduction of POGIL activities into lectures, with 83% broad agreement (defined as the percentage of responses in the 5-7 range on the 7-point scale used) with the statement that the trial lecture format was better than the traditional-style delivery used at that time to present Foundations of Chemistry lectures.

Table 1: Summary of Likert surveys for the August 2011 trial lecture (n=23)

Question	Mean Likert response (max. 7.0)	% Broad agreement
The lecture stimulated my enthusiasm for further learning.	6.0	96
In the lecture, I felt part of a group committed to learning.	6.3	96
It was made clear what was expected of me.	6.1	96
Working on activities in a group during the lecture was useful for my learning.	6.4	96
The lecture format motivated me to learn.	5.9	96
The lecture helped me to develop my thinking skills (e.g. problem solving).	6.2	96
I understand the concepts presented in this lecture.	6.6	100
The way this lecture was presented is better than the current format used for Foundations of Chemistry lectures.	5.7	83

Students' responses to the open-ended question 'What were the best aspects of the lecture and why?' indicated that they really enjoyed the small group work aspect of the trial lecture. For example:

"I liked the group work. It forces you to do the questions and in turn aiding your learning"

"Group activities make the work more relevant and easier to apply."

Comments provided in answer to the second open-ended response question 'This lecture format could be changed in the following ways to improve my learning' showed that students were mostly not in favour of a 2-hour lecture period. For example:

"Probably not a good idea to make it a 2 hr lecture as I think this is too long to maintain concentration."

However, some students responded well to the length of the trial lecture, as evidenced by the following comment:

"The lecture should be much longer, half for lecturer teaching the stuff and half for students to do group activities".

This comment also indicates the overall feeling of the group that a mixture of traditional lecture delivery accompanied by POGIL activities that link to the lecture content would be preferable to a 'pure' POGIL classroom. The positive response from this trial lecture to the introduction of POGIL reassured us that our choice of format for content delivery was appropriate, and enabled us to begin the development of the activities that were trialled in the two workshops that followed.

Results from workshops

The response to the three organic chemistry activities, even in their first iteration, from Foundations of Chemistry students who attended the November workshop was extremely positive (Table 2), with 100% broad agreement for all Likert statements.

Table 2: Summary of Likert surveys for the November 2011 workshop (n=5)

Question	Mean Likert response (max. 7.0)	% Broad agreement
The activities stimulated my interest in organic chemistry.	6.2	100
It was clear to me what to do in the activities.	6.0	100
The activities helped me to develop my thinking skills (eg, problem solving).	6.6	100
I understand the concepts presented in these activities.	6.4	100
Completing these activities has given me more confidence in approaching assessment tasks in organic chemistry.	6.6	100

Responses to the open-ended question ‘Overall, what was the best aspect of the activities and why?’ included:

“You can share ideas and learn from each other”

“Student involvement and participation and engagement. Problem-solving skills”

“A student can read anything, but when it comes down to doing questions and testing that knowledge, as done in these worksheets, that’s where the real learning happens.”

The responses to the survey for the April workshop, featuring a mixture of second year undergraduate and postgraduate students, were also extremely positive, with 100% broad agreement for all Likert statements (Table 3).

Table 3: Summary of Likert surveys for the April 2012 workshop (n=5)

Question	Mean Likert response (max. 7.0)	% Broad agreement
The activities stimulated my interest in organic chemistry.	6.4	100
It was clear to me what to do in the activities.	6.2	100
There was a strong inquiry focus to the activities.	6.6	100
The activities helped me to develop my thinking skills (eg, problem solving).	6.6	100
I understand the concepts presented in these activities.	6.6	100
The activities helped me better understand chemistry.	6.8	100

Responses to the open-ended question ‘Overall, what was the best aspect of the activities and why?’ included:

“Interactive. Keeps students focussed. Independent learning”

“They weren’t too long so I didn’t feel overwhelmed. There was a logical progression between parts”

“Learning by example/problem solving. Keeps you awake in lectures! Allows you to get a better grasp of the concepts by actually applying them.”

Results from the focus group

The focus group held after the April workshop resulted in a wide-ranging discussion between participants. It was clear that these students wanted to use their perspective as senior chemistry students to enhance the activities. The focus group participants all recognised the need to incorporate interactivity in lectures, and were extremely supportive of the introduction of this style of learning into the new Foundations of Chemistry courses, with one participant commenting:

“I wish my lectures were like that now.”

Additional comments during the focus group session further supported the use of inquiry-based learning:

“It definitely helps you to develop skills more than traditional lectures”

“What really helps with learning is that you are doing it yourself rather than the traditional where someone is telling you something and you take in one word out of every thirty.”

The group agreed that it would be beneficial if inquiry-based learning was introduced into science (not just chemistry) courses at higher year levels to support traditional lectures.

Implications for practice

Some of the biggest changes to the activities during the development process involved the removal of some content from the activities' Information sections. These changes were able to be made without any loss of content coverage as the content that was removed was able to be included on a lecture slide. This capability is a definite advantage to using the 'blended' POGIL classroom that we have adopted, which involves a mixture of activities and traditional lecturing. This method involves the lecturer presenting material from slides for 5-10 minutes before breaking for an activity. Time spent on each activity is no longer than 5-10 minutes, with longer activities occasionally split into two parts to enable discussion of earlier CTQs before completing the rest of the activity. At the conclusion of the activity, the class reconvenes and student input is requested. Once the activity is complete, the cycle begins again, with 5-10 minutes of lecture presentation, followed by time spent on activities. This blended approach allows for the content of activities and lecture slides to be fairly fluid and interchangeable while trying to find the right balance between activities and a traditional lecture presentation, rather than having to rely completely on the activities as the sole source of content.

The blended POGIL approach also solves issues brought up by students in the April workshop when commenting on ways the activities could be changed to improve their learning, with statements such as *“Brief explanation of concepts first before required to solve the problem”* and *“Need to provide with some more additional background prior to the activity”*. Because the POGIL activities were to be alternated with traditional lecture-style presentations, opportunities would be available for the teacher to provide students with background before beginning an activity, as well as emphasising any particular approaches it may be useful for students to take when working through the activity material. We realise that this approach is not a true POGIL classroom, but we have found that this middle ground is more acceptable to our cohort. Murphy, Picione and Holme (2010) reported using a

similar approach in chemistry classes after initially trialling a pure POGIL classroom, but subsequently found that a blended approach better suited the needs of their students. Teaching large chemistry classes using another type of blended POGIL approach has also been reported by Southam (2011), whereby classroom activities are continued in separate tutorial sessions and supported by pre-recorded mini-lectures available online.

Summary and conclusions

The use of workshops and a focus group to trial the activities and assist in their revision and development was extremely beneficial. The feedback from the workshops enabled us to improve and refine the activities based on the input from students who trialled the activities in a classroom setting. Participants in the workshops all seemed to find completing the activities an enjoyable experience that allowed them to interact with their peers to a far greater extent than if they were sitting in a traditional lecture. It was also clear that students appreciated being asked their opinion about the future direction of an undergraduate course, and relished the opportunity for their views to be heard. This real-world feedback was of great benefit in the overall construction and development of the activities and was found to be a useful approach to producing this type of teaching material.

This project began with the relatively simple aim of obtaining students' feedback in order to improve the teaching materials that we were preparing. This aim was certainly achieved; however, an unexpected side benefit was seeing the thoughtful nature with which the student volunteers approached this task in providing us with their views and ideas regarding not just the technical aspects of activity structure and content, but also the deeper concepts of how they approach their own learning, and the ways in which inquiry-based learning would be beneficial to them and to future students taking the course.

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Appendix 1 – Physical properties of alkanes POGIL activity

Activity 1.2 – How do the physical properties of alkanes change with size?

Table: Boiling point, molecular weight and physical state of selected alkanes

Alkane	No. of carbons	Molecular weight (g mol ⁻¹)	Boiling point (°C)	State at room temperature
Methane	1	16	-162	gas
Ethane			-89	gas
Propane			-42	gas
Butane			0	gas
Pentane			36	liquid
Hexane			69	liquid

Critical Thinking Questions

1. Complete the second column in the table, adding the number of carbons present in each alkane.
2. Describe the general trend in the boiling point of alkanes as the number of carbons increases.
3. Complete the third column in the table by calculating the molecular weight for each alkane.
4. How does the boiling point trend you described in CTQ 2 relate to the molecular weight of each compound?

Information

The boiling point of a liquid increases as the intermolecular forces between molecules increase.

Critical Thinking Questions

5. Based on your answers to CTQ 2 and 4, the information above and the data provided in the table, how do the intermolecular forces between molecules change as the molecular weight of an alkane increases?
6. Based on your answer to CTQ 4, in what physical state (solid, liquid or gas) would you predict the alkane icosane (molecular formula C₂₀H₄₂) to exist at room temperature? Explain your answer.

Appendix 2 – Introduction to alkenes and alkynes POGIL activity

Activity 1.3 – What are alkenes and alkynes?

Information

Alkanes are molecules that contain only carbon and hydrogen atoms joined by *single* bonds. Straight chain alkanes have the general molecular formula $C_nH_{(2n+2)}$. Molecules that contain one or more *double* bonds between *carbon* atoms are called **alkenes**. Molecules that contain one or more *carbon-carbon triple* bonds are called **alkynes**.

Table: Names and condensed structures of selected alkenes and alkynes

Name of alkene	Condensed structure	Molecular formula	Name of alkyne	Condensed structure	Molecular formula
ethene	$CH_2=CH_2$		ethyne	$HC\equiv CH$	
propene	$CH_2=CHCH_3$		propyne	$HC\equiv CCH_3$	
1-butene	$CH_2=CHCH_2CH_3$		1-butyne	$HC\equiv CCH_2CH_3$	
2-butene	$CH_3CH=CHCH_3$		2-butyne	$CH_3C\equiv CCH_3$	
1-pentene	$CH_2=CHCH_2CH_2CH_3$		1-pentyne	$HC\equiv CCH_2CH_2CH_3$	
2-pentene	$CH_3CH=CHCH_2CH_3$		2-pentyne	$CH_3C\equiv CCH_2CH_3$	
1-hexene	$CH_2=CHCH_2CH_2CH_2CH_3$		1-hexyne	$HC\equiv CCH_2CH_2CH_2CH_3$	
2-hexene	$CH_3CH=CHCH_2CH_2CH_3$		2-hexyne	$CH_3C\equiv CCH_2CH_2CH_3$	

Critical Thinking Questions

1. What is the suffix (end part of the word) common to the names of all alkenes?
2. What is the suffix common to the names of all alkynes?
3. Complete the third column in the table for the molecular formulae of the alkenes listed.
4. Based on your answer to CTQ 3, deduce the general molecular formula for an alkene.
5. Complete the sixth column in the table for the molecular formulae of the alkynes listed.
6. Based on your answer to CTQ 5, deduce the general molecular formula for an alkyne.
7. Using your derived general formulae from CTQ 4 and 6, what would be the molecular formula of
 - a) an alkene containing 19 carbon atoms?
 - b) an alkyne containing 32 carbon atoms?

8. Some of the alkene and alkyne names contain numbers. What do you think these numbers mean?
9. Based on your answer to CTQ 8, draw the condensed structure of 3-hexyne.
10. Why is there no such molecule as “methene”?

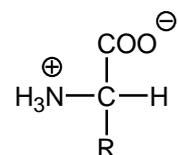
Appendix 3 – Proteins POGIL activity

Activity 3.3 – What are proteins?

Information – Biopolymers: Amino Acids to Proteins

Amino acids are the monomers that are used to build **proteins**. Proteins are essentially polyamides.

Note that amino acids contain both an acidic functional group (the carboxylic acid) and a basic functional group (the amine). This means that amino acids can effectively undergo acid-base reactions with themselves. As a consequence of this, α -amino acids are often written in the following way:



Something else to note is the fact that even though the above amino acid representation contains individual charges, each one cancels out the other, so that the molecule is still overall neutral in the same way as the representation given in your lecture notes. Amino acids and proteins usually exist in this *zwitterionic* form in neutral solution.

A protein's **primary** (1°) structure is the amino acid sequence of its peptide chain(s).

A protein's **secondary** (2°) structure is the local arrangement of a peptide's backbone atoms in three dimensions without regard to how the side chains are arranged.

A protein's **tertiary** (3°) structure refers to the three-dimensional structure of an entire peptide. The tertiary structure usually involves interactions among the individual side chains (R) on the amino acids comprising the protein.

Many proteins are composed of two or more peptide chains, referred to as *subunits*, which associate through noncovalent interactions (such as hydrogen bonds) and, in some cases, disulphide bonds. A protein's **quaternary** (4°) structure refers to the spatial arrangement of its subunits.

[Protein structure information adapted from Hanson (2007).]

Critical Thinking Questions

1. Draw the structure of the amino acid (in its **zwitterionic** form) where R is a CH₃ group.
2. Considering the acid-base properties of amino acids, what would the general structure of an amino acid look like in
 - a) an acidic solution?
 - b) a basic solution?

3. Which type of polymerisation reaction is used to attach the monomers to each other to produce peptides and proteins (hint: consult your lecture notes!)?
4. Draw a general representation of a peptide linkage.
5. Based on your answer to CTQ 4, draw the structure of a **dipeptide** (a peptide made from **two** amino acids) containing one amino acid where R is a CH_3 group and one amino acid where R is a $\text{CH}(\text{CH}_3)_2$ group. Draw your dipeptide in its **zwitterionic** form.
6. The protein haemoglobin consists of four subunits. Does the 3-dimensional arrangement of these subunits describe haemoglobin's primary, secondary, tertiary or quaternary structure? Explain.