The Biochemical Literacy Framework: Inviting pedagogical innovation in higher education

Danielle L. Evans¹, Sarah G. Bailey¹, Alfred E. Thumser¹, Sarah L. Trinder¹, Naomi E. Winstone² and Ian G. Bailey¹

¹ Department of Biochemical Sciences, University of Surrey, Guildford, UK
² Department of Higher Education, University of Surrey, Guildford, UK

Keywords
biochemistry; curriculum design; higher education; pedagogy; scientific literacy

Correspondence
I. G. Bailey, Department of Biochemical Sciences, University of Surrey, Guildford, Surrey, GU2 7XH, UK
E-mail: ian.bailey@surrey.ac.uk

(Received 7 February 2020, revised 22 June 2020, accepted 17 July 2020)

doi:10.1002/2211-5463.12938

When developing meaningful curricula, institutions must engage with the desired disciplinary attributes of their graduates. Successfully employed in several areas, including psychology and chemistry, disciplinary literacies provide structure for the development of core competencies—pursuing progressive education. To this end, we have sought to develop a comprehensive blueprint of a graduate biochemist, providing detailed insight into the development of skills in the context of disciplinary knowledge. The Biochemical Literacy Framework (BCLF) aspires to encourage innovative course design in both the biochemical field and beyond through stimulating discussion among individuals developing undergraduate biochemistry degree courses based on pedagogical best practice. Here, we examine the concept of biochemical literacy aiming to start answering the question: What must individuals do and know to approach and transform ideas in the context of the biochemical sciences? The BCLF began with the guidance published by relevant learned societies—including the Royal Society of Biology, the Biochemical Society, the American Society for Biochemistry and Molecular Biology and the Quality Assurance Agency, before considering relevant pedagogical literature. We propose that biochemical literacy is comprised of seven key skills: critical thinking, self-management, communication, information literacy, visual literacy, practical skills and content knowledge. Together, these form a dynamic, highly interconnected and interrelated meta-literacy supporting the use of evidence-based, robust learning techniques. The BCLF is intended to form the foundation for discussion between colleagues, in addition to forming the groundwork for both pragmatic and exploratory future studies into facilitating and further defining biochemical literacy.

The modern employment market means that graduates must be freethinking and adaptable [1], preparing for a career filled with challenges and change. To develop meaningful curricula, it is essential that institutions engage with the desired disciplinary attributes of their graduates. An aim is to develop individuals who are able to adapt through questioning and investigation to develop a career about which they are passionate and which they enjoy. Whilst biochemistry graduates have the potential to be biochemists, their development is not restricted to one career path, with biochemists fulfilling roles from technical and research to administrative and sales [2].

For undergraduate biochemistry students, biochemistry is simply the context in which key skills and attributes are learnt and developed. There is little concrete

Abbreviations
ASBMB, American Society for Biochemistry and Molecular Biology; BCLF, Biochemical Literacy Framework; BSCS, Biological Sciences Curriculum Studies; NUS, National Union of Students; QAA, Quality Assurance Agency; RSB, Royal Society of Biology.
restriction on the topics taught in an undergraduate biochemistry degree – paving the way for institutions to play to their strengths and produce engaging teaching around ‘hot topics’ at the forefront of research. However, in contrast to some current teaching practice at undergraduate level, skills should be taught in the context of disciplinary content knowledge [3,4]. Skills should be the focus, facilitating understanding including the development of connections between topics creating an independent, adaptable learner [5–7].

Teaching skills in the context of disciplinary knowledge could support evidence-based design for learning within programmes, focusing on the interconnections of biochemical knowledge, fostering lifelong learning skills and developing confident curious open-minded biochemists ready to integrate and participate in society. Individuals who are highly literate in the biochemical sciences can draw upon their skill set to apply themselves to new challenges as they desire with little constraint.

High-quality science education sustains a dynamic scientific community able to address global problems, and encourages an increased scientific literacy in the general population [8,9]. With these goals in mind, it is imperative that teaching and assessment strategies at all levels are approached with the same inquiry-driven, evidence-based approach as our scientific research, despite the challenges this may involve.

Bybee [10] and Shamos [11] proposed multiple levels of scientific literacy, increasing in complexity. The four levels suggested by Bybee [10] and the Biological Sciences Curriculum Studies (BSCS) [12] (Table 1) were one of the key theoretical frameworks underpinning the definition of chemical literacy [13] and thus inform our own approach to defining biochemical literacy.

**Existing disciplinary literacy frameworks**

Other disciplines have undertaken more advanced investigations into both best pedagogic practices, and literacy within their speciality – in particular, we have referred to existing research in chemistry, biology and psychology [14–19] – to inform the construction of the biochemical literacy framework (BCLF). For example, the development of biological literacy by the BSCS [12] produced the model of biological literacy, which shows the interaction between the four levels of scientific literacy given in Table 1. This model is shown in Fig. 1 and directed the format of the BCLF wherein interconnections were explicitly shown.

In these disciplinary frameworks, scientific literacy has been positioned as being underpinned by disciplinary literacy [13]. It is important to note that attainment of high scientific literacy does not mean an individual always has high disciplinary literacy. For example, a geologist can be scientifically literate, but not biochemically literate, and vice versa. Scientific literacy crosses the disciplines, whereas disciplinary literacy does not. Scientific literacy and the importance of scientific literacy to the general population are discussed later.

When examining these literacies, we learnt that there is unlikely to be a ‘one-size-fits-all’ approach with such a diverse and multidisciplinary topic as biochemistry, with both chemistry and biology remaining active areas of pedagogic discussion [20–22] and innovation [23–26]. This approach aligns with the Quality Assurance Agency (QAA) and Royal Society of Biology (RSB) guidance – with neither aiming to provide a prescriptive curriculum, but encouraging creativity and innovation [27,1].

There are several existing concept inventories for the biochemical sciences, most notably the work of Loertscher et al. [28] on identifying the threshold

| Table 1. The scale of scientific literacy, suggested by [10] and [12], as adapted from [13]. |
|---------------------------------------------------------------|
| **Scientific literacy categories** | **Definitions** |
| Scientific illiteracy | Students who cannot relate to, or respond to a reasonable question about science. They do not have the vocabulary, concepts, contexts or cognitive capacity to identify the question as scientific |
| Nominal scientific literacy | Students recognise a concept as related to science, but the level of understanding clearly indicates misconceptions |
| Functional scientific literacy | Students can describe a concept correctly, but have a limited understanding of its application. |
| Conceptual scientific literacy | Students develop some understanding of the major conceptual schemes of a discipline and relate those schemes to their general understanding of science. Procedural abilities and understanding of the processes of scientific inquiry and technological design are also included in this level of literacy. |
| Multidimensional scientific literacy | This perspective of scientific literacy incorporates an understanding of science that extends beyond the concepts of scientific disciplines and procedures of scientific investigation. It includes philosophical, historical and social dimensions of science and technology. Here, students develop some understanding and appreciation of science and technology regarding its relationship to their daily lives. More specifically, they begin to make connections within scientific disciplines, and between science, technology and the larger issues challenging society. |
concepts for biochemistry. However, no consensus on the key skills underpinning the biochemical sciences is readily available to educators. To this end, we have sought to develop a comprehensive blueprint of a graduate biochemist, providing detailed insight into the development of skills in the context of disciplinary knowledge. This is intended as a foundation document, with an invitation to colleagues to further develop these, in order that biochemistry curricula are developed for high quality, capable and independent graduates.

The overall aim of when formulating the BCLF was to construct a clear framework of the capabilities composing ‘Biochemical Literacy’. We aimed to achieve this through two objectives: firstly, collating the key capabilities embedded within guidance published by learned societies relating to the development of undergraduate Biochemical Sciences programmes, and identifying themes within and across documentation; and secondly, identifying literature relevant to each theme, utilising systematic literature searching techniques in order to provide clarity and depth to the framework.

The BCLF could prove invaluable in assisting the production of higher quality courses by initiating discussion among those developing biochemical degree courses, in particular regarding pedagogic best practices as the foundation of the curriculum. There are several pedagogical approaches implicitly supported by the framework due to their alignment with the idea of teaching skills in the context of content knowledge [29,30]. These move teaching methods towards student-centred learning – actively involving students in their education and facilitating lifelong learning practices [6].

**Materials and methods**

The data for this study consisted of guidance documents published by the scholarly, statutory and specialist organisations: the QAA, RSB, the Biochemical Society,
Advance HE (previously known as the Higher Education Academy) and the American Society for Biochemistry and Molecular Biology (ASBMB). These represent the main sources of reference for the creation and content of undergraduate biochemistry courses in UK Higher Education Institutions and are all available in the public domain. Each of these documents has undergone development and/or validation processes as detailed in Table 2.

Additional material was identified when referring to the bibliographies of guidance provided by relevant organisations, before finally additional scholarly guidance were identified through a series of searches utilising the online databases PubMed, ERIC and Google Scholar. Only literature written in the English Language where the full text was available, or obtainable within the study time frame through interlibrary requests were included.

Thematic analysis provided both the overarching concepts, and much of the detail present in the BCLF. The data were coded inductively, identifying key words common to all documentation beginning with the UK QAA subject benchmark statement for the biosciences [27] then moving to the more disciplinary-specific guidance. The common key terms were grouped, using a concept mapping [31–33] approach to develop succinct overviews of areas derived from multiple sources of literature. A ‘bigger picture’ order was developed by considering overlapping and associated elements across multiple concept maps. These thereafter went through many stages of reduction aiming for clarity of communication without compromising quality before producing the final framework. Comprehensibility was considered at every stage, therefore informing subsequent stages. This facilitated the identification and organisation of the forming seven skill areas underpinning biochemical literacy.

Table 2. The development and/or validation processes of the undergraduate Biochemistry Curriculum guidance documentation, collated from each individual guidance source – citations embedded for clarity.

| Guidance document                        | Development and/or validation processes                                                                 |
|-----------------------------------------|-------------------------------------------------------------------------------------------------------|
| RSB accreditation                       | Initial (2010) input from: universities, business and industry, government, learned societies, research councils, funding bodies and sector skills councils. Two-year consultation period, including a survey of undergraduate, postgraduate and recent graduate students of the life sciences. As of 2018, accreditation conference attendees input into the accreditation quinquennial review via round table discussions [69,129] |
| QAA parts and chapters                  | Consultation with higher education providers; their representative bodies; the NUS, professional, statutory and regulatory bodies; and other interested parties [130] |
| QAA subject benchmark statement: biosciences | Produced by a group of subject specialists drawn from, and acting on behalf of, the subject community. This then goes through a full consultation with the wider academic community and stakeholder groups, all facilitated by the QAA [27] |
| ASBMB                                   | Five-phase project involving disciplinary experts and students, in addition to high school, college and university educators. This process was undertaken by Loertscher et al. funded by the National Science Foundation (NSF) and is detailed in [28] |

Results and Discussion

Building on our interpretation of literacy, we begin to explore it in the context of the biochemical discipline. Defining the skills and foundational knowledge underpinning disciplinary literacy is complex and multifaceted [18] due to the complex nature of skills and knowledge with their many interconnections. The disciplinary literate individual possesses skills for lifelong learning in their field of study and their literacy comprises multiple core interacting skills, which we have grouped as following: [34,35]

- Critical thinking
- Communication
- Self-management
- Information literacy
- Visual literacy
- Practical skills
- Content knowledge

The grouping of these skills is almost immaterial beyond assisting clarity of communication – what matters is how they interact, that is their connections together with the discussion they elicit when designing and planning a course of learning. These connections are illustrated in Fig. 2 following a concept map format. Interactions between these core skills are keys because progression in one can permit new perspectives, transforming understanding. Without these skills, limits upon learning and development are imposed upon the individual.
Critical thinking: a contextual, self-improving process

Rigorous, well-evidenced and inquiry-based evaluation is fundamental to ‘thinking like a scientist’ [36–38]. Undergraduates are encouraged to question everything from information, to conclusions and points of view [39–41]. An essential part of this is the determination of the scientific integrity of information, by ensuring that robust and unbiased methodology is present, both in the work of others and in their own [35,42,43].

This self-improving cycle of ‘scientific thinking’ is supported by the general principles of ‘critical thinking’ [42,44,45]. Whilst critical thinkers are found outside the sciences, the inwardly evaluative nature of scientific enquiry means that the development of critical thinking skills is well grounded in STEM curricula [36,39].

Critical thinking has been discussed by several within the Scholarship of Teaching and Learning in relation to the biosciences [46,47]. However, we find the most complete, clear and robust definition is offered by Scheffer et al. [48] who examined the concept using the Delphi technique, thus generating both discussion and judgement on the topic of critical thinking from multiple experts, which is summarised in Table 3. The differences between critical thinking in nursing, or any other discipline, and biochemistry are fundamentally the context in which they are learnt and developed. For example, a biochemist may develop their critical thinking skills when engaging in a teaching laboratory exercise; perseverance for example is needed when facing challenges, reflection when discovering a result which does not fit with their previous knowledge of a concept, and so on.

To a biochemist, critical thinking could be considered as an independent, controlled, self-monitored and self-improving process forming the foundation for all other skills [6,39,44,48]. Critical thinking itself is highly contextual [49], and a simple definition may be considered as:

---

![Figure 2: Biochemical Literacy](image)

**Fig. 2.** Biochemical literacy. A concept map illustrating the core-interacting skills forming the foundation of biochemical literacy.
Critical thinking, like many other skills, cannot be learnt easily and must be practised regularly to form the habits of mind necessary [44,51,52]. It has been reiterated by both Ennis [52] and Gelder [51], among others, that practice in varied contexts and manners is important to develop the transferable aspect of the skill; this is needed to achieve the overall aim of increased scientific literacy [53]. For biochemists, this could mean that thought should be given to the development of critical thinking skills in the laboratory environment due to the requirement for critical analysis of experimental design and experimental data, as well as problem-solving – a distinct but associated higher-order thinking skill [44]. Problem-solving in a laboratory environment is essential in order to improve laboratory experiments experiencing technical issues [54,55]. Therefore, due to the utilisation of laboratory experiments in furthering knowledge and understanding in both learning and research environments, problem-solving is a key element of biochemical literacy [56–58].

### Information literacy: a foundation for lifelong learning

Graduates in biochemistry are encouraged to come to evidence-based conclusions and thus must be able to use sources of information effectively to inform their decision. This does not mean that every biochemist will come to the same conclusion; however, they should be able to defend their position whilst recognising the transient nature of knowledge, using evidence gathered through thorough critical analysis of information assembled efficiently from a variety of relevant and robust sources. Facilitating this process is information literacy, the subcomponents (including interactions) of which are illustrated in Fig. 4 as a concept map and discussed below [43,50,59–62].

Individuals in any discipline benefit greatly from drawing upon established knowledge to inform their actions both at work and in their personal lives [44,48,63]. Drawing upon critical thinking skills, identifying what and why information is needed is often the first step in any project, and is the first step in Fig. 4 [61,64].

### Locating information

Being able to locate information competently is essential to allow individuals to inform and expand their learning. A modern graduate must be able to confidently use the tools available to them (linking with technology skills) to learn from a wide range of materials [43,62].

---

**Table 3.** The skills composing critical thinking and their definitions, adapted from Scheffer et al. [48].

| Skills            | Definition                                                                 |
|-------------------|---------------------------------------------------------------------------|
| **Habits of the mind** | Assure of one’s reasoning abilities                                      |
| Confidence        | Intellectual inventiveness used to generate, discover or restructure ideas; imagining alternatives |
| Creativity        | Capacity to adapt, accommodate, modify or change thoughts, ideas and behaviours |
| Flexibility       | An eagerness to know by seeking knowledge and understanding through observation and thoughtful questioning in order to explore possibilities and alternatives |
| Inquisitiveness   | Seeking the truth through sincere, honest processes, even if the results are contrary to one’s assumptions and beliefs |
| Intellectual integrity | Insightful sense of knowing without conscious use of reason               |
| Intuition         | A view point characterised by being receptive to divergent rules and sensitive to one’s biases |
| Open-mindedness  | Pursuit of a course with determination to overcome obstacles              |
| Perseverance      | Contemplation upon a subject, specially one’s assumptions, and thinking for the purposes of deeper understanding and self-evaluation |
| Reflection        | Separating or breaking a whole into parts to discover their nature, function and relationships |
| Analysing         | Separating or breaking a whole into parts to discover their nature, function and relationships |
| Applying standards | Recognising differences and similarities among things or situations and distinguishing carefully as to category or rank |
| Discriminating   | Searching for evidence, facts or knowledge by identifying relevant sources and gathering objective, subjective, historical and current data from these sources |
| Information seeking | Drawing inferences or conclusions that are supported in or justified by evidence |
| Logical reasoning | Envisioning a plan and its consequences                                  |
| Predicting        | Changing or converting the condition, nature, form or function of concepts among contexts |
| Transforming      |                                                                 |

Determining connections to make evidenced-based conclusions whilst utilizing evaluation and amalgamation of information [35,50]

We have illustrated this in Fig. 3, which shows a skeletal overview of related principles. This may provide a useful tool in developing students’ critical thinking skills, which they may then use to address information from all sources.
A literature search begins the information retrieval process, employing a variety of techniques discussed elsewhere [65,66], and informs the directions and/or methods for research projects. Outside of academia, literature searching is a key skill which when appropriately and robustly applied can streamline the process of finding the most relevant and accurate information to the topic of interest.

Analysis, evaluation and organisation of information
As illustrated in Fig. 4, both information organisation and evaluation/analysis occur both concurrently, and in sequence. Continual critical evaluation of information allows robust conclusions to be formed and is vital in both academia and real-world situations [39,43]. During a literature search, the individual will continually evaluate the information for relevance and reliability, whilst organising the pertinent information and tracking key concepts. Information can be organised utilising reference management software, drawing upon technology skills and self-management. This continual evaluation and analysis of information facilitates the creation of connections between ideas, leading to greater understanding – again drawing on critical thinking.

Visual literacy
Information can come in many forms, and sources are not restricted to written information. Interpreting information communicated in external representations such as graphs and infographics draws upon ‘visual literacy’. As in information literacy, a critical approach to interpreting external representations of information facilitates building a meaningful understanding of knowledge [67].

Offerdahl et al. [68] argued that visual literacy can be considered especially important to biochemists due to the high volume of visual external representations used in the discipline due to the highly complicated systems revealed through modern methods [28,67]. They additionally make the case that by explicitly including teaching based around developing visual literacy skills, students are more readily able to use non-written sources of information to develop and communicate their understanding of biochemical knowledge – becoming more fluent in discipline-specific discourse and by extension, more biochemically literate [68]. The relationships between molecular form and function are key to understanding content for biochemists [69]. Thus, visual literacy development must not be restricted solely to interpretation and creation of external representations, but also to the individuals innate understanding of a 3D world. It is on this basis that visual literacy has been explicitly included within the BCLF.

Intellectual property and information use
During use of information, an understanding and avoidance of plagiarism through citation and
awareness of intellectual property is vital. Plagiarism at graduate level is a contentious issue that often makes the national news. In addition, only 40% of UK higher and further education students surveyed by the National Union of Students (NUS) in 2012 considered their knowledge of intellectual property to be sufficient to support them in their future career [70].

Communication

In the modern world, with its technological advances and cross-disciplinary work, good communication and collaboration skills are essential. Good communication facilitates change, through collaborations borne out of mutual understanding, and thus is applicable whilst learning, throughout a career and in life. All of the biochemical course guidance places an emphasis on these skills, as critical for the graduate biochemist – regardless of their postgraduate choices [27,71].

Communication encompasses a wide range of skills, including the use of language (such as appropriate use of discipline-specific nomenclature), listening skills [72] and using an appropriate format – whether that is written, oral or visual. Science communication facilitates understanding, enabling informed decision-making [73]. This is particularly important with the use of social media breaking down access to and engagement with science [74,75], and politics becoming more interwoven through policies based upon and affecting research [76,77]. Therefore, the communication of scientific information in a format and language appropriate to the audience is a skill that can arguably benefit society as a whole [78-81].
Self-management

There are several skills underpinning self-management as illustrated in Fig. 5 as a concept map. Self-management along with autonomy and self-discipline constitutes three desirable employee characteristics [82]. Self-management is referred to repeatedly in the QAA, RSB and Biochemical Society guidance – from ‘self-learning’ and ‘project management’ in the RSB Accreditation documentation [1], to ‘independent learning skills’, the ability to ‘identify and work towards targets’ and being able to ‘evaluate their own performance’ in the QAA Subject Benchmark Statement for Biosciences [27].

Effective self-management may help in avoiding stress by controlling and directing aspects of learning, as in project management, drawing upon time management skills such as prioritisation and planning. Without organisational and self-management skills, an individual may struggle to engage fully in the self-directed learning critical to remaining up-to-date in a discipline [83,84]. Individuals with good self-management skills may be considered more proficient in their laboratory skills where timing and organisation is essential. These skills are often necessary to complete a biochemistry course with their assessment deadlines and laboratory skill elements, and however, not all students will enter at the same level; therefore, self-management skills must also be explicitly developed [82,83].

Self-improvement is also a factor of self-management, and as shown in Fig. 5, which relies upon and is facilitated by feedback literacy. Whilst students most likely will have received feedback prior to university, students may begin their biochemistry programmes without having been supported to use feedback effectively [85,86].

Research suggests that directly training students to manage and use feedback productively can lead to an increase in students’ self-reported feedback literacy [87]. Feedback literacy may not seem to be at the forefront of biochemical priorities when teaching; however, Quinton and Smallbone [88] argue that for ‘learning from feedback to be most effective, programmes should be designed to include classroom time allocated for reflection on written feedback’. The feedback given in such sessions should be timely and accurate [44,51],

Fig. 5. Self-management concept map illustrating elements of self-management, including those which support self-improvement.
in addition to both easy to understand, and highly applicable in order to optimise learning outcomes [87,89]. Winstone and Millward [90], and Shute [91] discuss the importance of formative feedback, noting several of the advantages as: providing future modification and development guidance; affecting student motivation by highlighting the gap between where the student is, and where the student needs to be; and fulfilling the student demand for feedback which supports a deeper understanding of the subject.

There are three key elements to appreciating feedback purpose and processes and thus increasing feedback literacy: [87,92]

- Making judgements about the quality of work
- Managing emotion in response to feedback
- Taking meaningful action on feedback

All the elements of feedback literacy should be considered when aiming to facilitate biochemical literacy as without the capacity to identify actions to improve, students may stagnate in their learning.

**Practical skills**

There are many practical elements underpinning the biochemical sciences [27]. These are discussed below in detail, but generally support the deeper and more interconnected understanding of biochemical content knowledge.

**Laboratory skills**

The biochemical graduate benefits from good laboratory skills – these skills underpin drug discovery, diagnostic services and the development of consumer goods (e.g. cosmetics, functional foods and cleaning supplies) [93]. Laboratory skills have many elements, which may be best represented in the three domains proposed by Zaghloul [94]: the cognitive domain, the affective domain and the psychomotor domain. The cognitive domain (i.e. how the student’s cognitive activities are structured as based on Bloom’s taxonomy [95,96]) links with biochemical content knowledge, in addition to several of the other skills discussed under ‘practical skills’ such as data management, health and safety, and research methods and methodology. The affective domain encompasses the student attitude towards the content knowledge, their education and the laboratory activities – these again link strongly health and safety, in addition to equipment handling. Good laboratory skills must include a grounding in using basic equipment (including but not limited to: a pipette, a microscope, the centrifuge and a spectrophotometer) and following common procedures (including but not limited to: cell culture, aseptic technique, chromatography and electrophoresis) [27]. Finally, facilitating the development of the psychomotor domain, that is, the coordination between the students’ brain and body [94], is essential to supporting accurate and precise laboratory practices.

The exact laboratory skills a biochemical graduate should have at their disposal are likely to change frequently with advances in analytical techniques. However, the literate graduate would be confident enough in their laboratory practices to adapt, with appropriate training, to new methods and equipment. These laboratory skills are likely to draw upon technological skills, psychomotor skills, creativity and critical thinking skills in order to support the most adaptable and versatile graduates.

**Technology skills**

The capability for adaption is key in this technologically fast moving era [97]. Adaption to new and emerging technologies, new opportunities and existing technology to new applications are all commonly expected of individuals – both in and out of the workplace [97–100]. Therefore, graduates in all disciplines must be able to confidently and competently use technology – in particular, to assist in processes such as data management and analysis [101]. Explaining computational ideas in the context of biology could be taught authentically utilising bioinformatics methodology as the context; bioinformatics is an important skill utilised by the modern biochemist, and it is recommended to be taught at the undergraduate level [102–106].

Online information seeking has been shown to be without depth in the ‘Google Generation’ (born post-1993), and therefore, appropriate levels of technological skills should not be assumed in undergraduates – these skills that can be, and need to be taught [43,107]. Technological skills can be developed alongside other attributes as integrating skills into meaningful tasks is key to disciplinary literacy [108]. For example, statistical analysis of laboratory results to disseminate in a conference-style poster would draw upon critical thinking, creativity, communication (including presentation), numeracy and technology use.

We have focused little on defining exact technology skills required for the biochemical graduate – this is because, like biochemical literacy, technological literacy is underpinned by cognitive skills we earlier grouped under ‘critical thinking’ [109]. This further supports the notion that key skills should be the focus of educational planning for graduates in the biochemical sciences.
of educational courses, with subject-specific knowledge simply the context in which these skills are learnt.

Research methods and methodology

An understanding of research methods and methodology facilitates the understanding of scientific processes by enabling the development of connections as well as supporting the logical analysis of information [5,110,111]. A greater scientific literacy can be attained by exposing learners to the language common in research – useful to both future ‘users’ and ‘consumers’ of research [110,111]. Teaching research methods and methodology are more than just exposure to biochemical discourse; it also aims to build a critical approach to attaining and testing knowledge essential to the successful biochemical graduate. Proposing and testing hypotheses is also applicable beyond academic life, allowing the construction and understanding of new knowledge facilitating informed decision-making [5,111]. During the design and undertaking of experiments, consideration must be given to validity, accuracy, calibration, precision, duplicability, appropriate use of controls and possible sources of uncertainty or bias.

When testing a hypothesis, consideration must be given to ethics at all levels. Ethics promote truth and minimise error – for example by prohibiting fabrication, falsification or misrepresentation of data [112,113]. Ethics also protect intellectual property interests whilst still encouraging collaboration by promoting ‘trust, accountability, mutual respect and fairness’ [112]. National and international laws on the conduct of research (particularly involving animal or human subjects) help to promote and enforce an ethical research environment [112,114]. Due to all of these reasons, and more, ethics must be embedded into the teaching of research and research methodology, and biochemistry.

Data management

Linking with practical laboratory skills are data management skills. Data management is required on several scales as a biochemist – from the physical organisation of stored samples, and the maintenance of a laboratory book to large data sets and meta data. The appropriate transformation, analysis and interpretation of experimental data using either/both qualitative and quantitative techniques involve the use of good numeracy skills [27,115].

Numeracy skills are vital for on-the-go calculations in the laboratory environment; therefore, these skills must also be taught and reinforced. To facilitate analysis of data, the use of statistical programmes and spreadsheets is beneficial – again linking with technological skills.

Health and safety

Grouped under research methods and methodology are the health and safety considerations that must underpin testing and laboratory skills. These are vital for the undergraduate biochemist to participate in laboratory-based learning tasks, as well as for the graduate biochemist in a research or specimen analysis role. The fundamental idea of ‘risk assessment and minimising risk’ learnt in the laboratory applies widely in workplaces across industry sectors, with consideration given not just to one’s own health and safety, but the health and safety of others too. A variety of teaching methods can be used to educate in health and safety [116,117], but it is a vital aspect of all undergraduate biochemistry courses, and thus is included in the BCLF. The topics that may be covered under health and safety include Control of Substances Hazardous to Health assessments and the use of Personal Protective Equipment.

Content knowledge – a conceptual perspective

Biological knowledge is complex, progressing alongside scientific advances and giving rise to a dynamic and changing discipline. Much of taught knowledge is conceptual rather than specific, and these concepts are illustrated with examples to enhance perspective and comprehension [28]. To understand the biological sciences is to have an ‘understanding of the processes and mechanisms of life’ [27], from the molecular to the cellular and beyond. Due to the many inter-relationships inherent in studying the processes and mechanisms of life, the biological sciences are underpinned by chemistry, mathematics and physics in addition to the data analytics and information technology skills previously discussed.

Due to the unique viewpoint biochemists utilise, biochemistry requires a strong foundation in chemistry; chemical principles relate to important biochemical concepts, therefore enabling more complete understanding and deeper study. Not all students enter university with the same grounding in chemistry, thus ensuring the basics are embedded early in courses (though these do not have to be in chemistry-specific modules/courses [118]) is vital in strengthening and supporting key concepts across a wide range of interacting subdisciplines including physiology, genetics, microbiology and pharmacology.
Biochemistry uses chemical knowledge and techniques to understand and solve biological problems, focusing on biological processes within and related to living organisms. ‘Science is not a body of information to be mastered, but rather a way to construct new knowledge’ [5]. For example, biochemists use their understanding of how structure relates to function in a molecule to predict how that molecule will interact within a biological system. A conceptual approach to knowledge helps to facilitate these cross-disciplinary interpretations, and there are several ‘key concepts’, which provide a good foundation for cross-disciplinary learning [119–121].

Identifying key concepts

Several key concepts are mentioned in each course content guidance document examined – we have identified and categorised these for clarity during discussions in Fig. 6.

Each of the guidance documents referred to five key concepts – homeostasis, biochemical reactions, structure and function, evolution and information storage. These five key concepts are not categorical and interact with each other – for example, the structure of a molecule determines its function, which may be as a catalyst in a biochemical reaction. The sub-concepts were chosen from the guidance to give an indication of the scope of the key concept; however, teaching should highlight the interactions to provide a more comprehensive and authentic understanding of biochemical knowledge [122,123]. Further exploration of the key concepts of biochemistry may benefit curriculum design and have already begun [120,124–126].

Conclusion

The term ‘scientific literacy’ has been in use for many decades, with several definitions. Scientific literacy is the ability to ‘make use of scientific knowledge in real-world situations’ [127], that is both not limited to academia and touching upon the importance of scientific literacy in everyday life for every citizen. Holbrook and Rannikimae [55] discuss the varying definitions proposed, and identified the defining concept as ‘Scientific literacy is not simply reliant on the acquisition of content’. This is the underpinning concept of the BCLF and the basis of the representation of skills leading to the understanding of biochemical content knowledge in Fig. 2. It is intended that this framework be used to pragmatically approach the complex nature of curriculum design in the biochemical sciences within higher education institutions.

The seven skills (critical thinking, information literacy, visual literacy, self-management, communication, practical skills and content knowledge) of the biochemically literate individual proposed here are not intended to be an unchangeable, rigid framework for curriculum design. Their interaction and connections are far more important than the categories in which they have been placed for clarity of communication. This is intended to support the creation of evidence-based programmes of learning – focusing on the interconnections of biochemical knowledge, fostering lifelong learning skills and developing confident curious open-minded biochemists. We intend that this proposed framework be utilised as the basis of discussion and innovation when developing biochemical curricula constructed around the idea of ‘skills in the context of disciplinary content knowledge’.

Future work will include the exploration of academic, student and industry definitions of biochemical literacy (overall, and by dimension) with the particular aim to validate the current proposal in line with the other disciplines discussed. Additionally, responses to the proposed BCLF will be invited to explore where further work might be directed.
Acknowledgements

Thank you to Professor John H. McVey (University of Surrey, UK) for your insightful comments when proofreading this work, the limitations of which are our responsibility as authors. We would like to acknowledge our gratitude to the School of Bioscience and Medicine at the University of Surrey, UK, for funding the PhD of the first author.

DLE received a PhD Scholarship from the School of Biosciences and Medicine, University of Surrey. The funder had no role in study design; in the collection, analysis or interpretation of data; in the writing of the report; or in the decision to submit the article for publication.

Conflict of interest

The authors declare no conflict of interest.

Data accessibility

All data used in the creation of this manuscript are available in the public domain.

Author contributions

DLE, IGB, NEW, AET, SGB and SLT involved in the conceptualisation. DLE performed the data curation, resources and investigation, and involved in the project administration and visualisation. IGB, NEW, SGB, SLT and AET involved in the funding acquisition. DLE, IGB, NEW and AET performed the methodology. IGB and NEW involved in the supervision. DLE, IGB, NEW and SGB wrote original draft preparation. DLE, IGB, NEW, SGB and SLT reviewed and edited the manuscript.

References

1 Royal Society of Biology (2015) The Degree Accreditation Handbook. Technical report, Royal Society of Biology, London.
2 Higher Education Statistics Academy (2018) Higher Education Leavers Statistics: UK, 2016/17 - Outcomes by subject studied.
3 Momsen JL, Long TM, Wyse SA and Ebert-May D (2010) Just the facts? Introductory undergraduate biology courses focus on low-level cognitive skills. CBE Life Sci Educ 9, 435–440.
4 Watts M and Becker WE (2008) A little more than chalk and talk: results from a third national survey of teaching methods in undergraduate economics courses. J Economic Educ 39, 273–286.
5 de Ávila P and Torres BB (2010) Introducing undergraduate students to science. Biochem Mol Biol Educ 38, 70–78.
6 Nair SP, Shah T, Seth S, Pandit Nand Shah GV (2013) Case based learning: a method for better understanding of biochemistry in medical students. J Clin Diagn Res 7, 1576–1578.
7 Shanahan T and Shanahan C (2012) What is disciplinary literacy and why does it matter? Top Lang Disord 32, 7–18.
8 van Eijck M and Roth W-M (2007) Improving science education for sustainable development. PLoS Biol 5, 2763–2769.
9 Nurse P (2016) The importance of biology education. J Biol Educ 50, 7–9.
10 Bybee RW (1997) Towards an understanding of scientific literacy. In Scientific Literacy. An International Symposium (Gräber W and Bolte C, eds), pp. 37–68. Institut für die Pädagogik der Naturwissenschaften (IPN), Kiel.
11 Shamos MH (1995) The Myth of Scientific Literacy. Rutgers University Press, New Brunswick, NJ.
12 Biological Sciences Curriculum Studies (1994) Developing Biological Literacy: A Guide to Developing Secondary and Post-Secondary Biology Curricula. Kendall Hunt Publishing, Dubuque, IA.
13 Shwartz Y, Ben-Zvi R and Hofstein A (2006) The use of scientific literacy taxonomy for assessing the development of chemical literacy among high-school students. Chem Educ Res Pract 7, 203–225.
14 Chittleborough G (2014) The development of theoretical frameworks for understanding the learning of chemistry. In Learning with Understanding in the Chemistry Classroom, chapter 2, 1 edn (Devetak I and Glazar SA, eds), pp. 25–41. Springer Science+Business Media B.V., Berlin.
15 National Council of Teachers of English (2013) NCTE position statement: The NCTE definition of 21st century literacies.
16 Murdoch DD (2016) Psychological literacy: proceed with caution, construction ahead. Psychol Res Behavior Manage 9, 189–199.
17 Ordman AB (2009) Scientific literature and literacy: a course of practical skills for undergraduate science majors. J Chem Educ 73, 753.
18 Fang Z and Coatoam S (2013) Disciplinary literacy: what you want to know about it. J Adolesc Adult Lit 56, 627–632.
19 Fang Z (2013) Disciplinary literacy in science. J Adolesc Adult Lit 57, 274–278.
20 Cooper MM, Posey LA and Underwood SM (2017) Core ideas and topics: building up or drilling down? J Chem Educ 94, 541–548.
21 Crowe A, Dirks C and PatWenderoth M (2008) Biology in bloom: implementing Bloom’s taxonomy to
enhance student learning in biology. CBE Life Sci Educ 7, 368–381.
22 Kim MK, Patel RA, Uchizono JA and Beck L (2012) Incorporation of Bloom’s taxonomy into multiple-choice examination questions for a pharmacotherapeutics course. Am J Pharm Educ 76, 114.
23 Broman Kand Parchmann I (2014) Students’ application of chemical concepts when solving chemistry problems in different contexts. Chem Educ Res Pract 15, 516–529.
24 Yuriev E, Capuano B and Short JL (2016) Crossword puzzles for chemistry education: learning goals beyond vocabulary. Chem Educ Res Pract 17, 532–554.
25 Marcondes FK, Moura MJCS, Sanches A and Costa R, de Lima PO, Groppo FC, Amaral MEC, Zeni P, Gaviao KC and Montreorz LH (2015) A puzzle used to teach the cardiac cycle. Adv Physiol Educ 39, 27–31.
26 Quillin K and Thomas S (2015) Drawing-to-learn: a framework for using drawings to promote model-based reasoning in biology. CBE Life Sci Educ 14, es2.
27 The Quality Assurance Agency for Higher Education (2015) Subject Benchmark Statement - Biosciences. Technical report, The Quality Assurance Agency for Higher Education, Gloucester.
28 Loertscher J, Green D, Lewis JE, Lin S and Minderhout V (2014) Identification of threshold concepts for biochemistry. CBE Life Sci Educ 13, 516–528.
29 Johnson RJ (2017) Arsenic-based Life: an active learning assignment for teaching scientific discourse. Biochem Mol Biol Educ 45, 40–45.
30 Boyd-Kimball D and Miller KR (2018) From cookbook to research: redesigning an advanced biochemistry laboratory. J Chem Educ 95, 62–67.
31 Kinchin IM (2011) Visualising knowledge structures in biology: discipline, curriculum and student understanding. J Biol Educ 45, 183–189.
32 Novak JD (1995) Concept mapping: a strategy for organizing knowledge. In Learning Science in the Schools: Research Reforming Practice (Glynn SM and Duit R, eds), pp. 229–245. Lawrence Erlbaum Associates, Inc., Hilldane, NJ.
33 Novak JD and Cañas AJ (2008) The Theory Underlying Concept Maps and How to Construct and Use Them. Technical report, Florida Institute for Human and Machine Cognition, Pensacola, FL.
34 Evers T (2015) Literacy in all Subjects.
35 Ventura M, Lai E, and Dicerbo K (2017) Skills for Today, What We Know about Teaching and Assessing Critical Thinking.
36 Bauer-Dantoin Angela (2008) The Evolution of Scientific Teaching Within The Biological Sciences. In Exploring Signature Pedagogies: Approaches to Disciplinary Habits of Mind (Gurung RAR, Chick NL and Haynie A, eds). Stylus Publishing, Sterling, VA.
37 Morris BJ, Croker S, Zimmerman C, Gill D and Romig C (2013) Gaming science: the "Gamification" of scientific thinking. Front Psychol 4, 1–16.
38 DeHart Hurd P (2002) Scientific literacy: new minds for a changing world. Sci Educ 82, 407–416.
39 Twitchell S (2007) The "aha!" Approach or Critical Thinking and Understanding Concepts. volume 34, 7th edn. Foundation for Critical Thinking, Tomales, CA.
40 Hmelo-Silver CE, Duncan RG and Chinn CA (2007) Scaffolding and achievement in problem-based and inquiry learning: a response to Kirschner, Sweller, and Clark (2006). Educ Psychol, 42, 99–107.
41 Krajcik JS and Sutherland LM (2010) Supporting students in developing literacy in science. Science 328, 456–459.
42 Stowe RL and Cooper MM (2017) Practicing what we preach: assessing "Critical Thinking" in organic chemistry. J Chem Educ 94, 1852–1859.
43 Welsh T and Wright M (2010) What is information literacy? In Information Literacy in the Digital Age: An Evidence-Based Approach, chapter What is In, 1 edn, pp. 1–11. Elsevier Science, Oxford.
44 Mulnix JW (2012) Thinking critically about critical thinking. Educ Philos Theory 44, 464–479.
45 Murtonen M and Balloo K, eds (2019) Redefining Scientific Thinking for Higher Education: Higher-order Thinking, Evidence-based Reasoning and Research Skills. London, UK: Palgrave Macmillan.
46 Rowland SL and Myatt PM (2014) Getting started in the scholarship of teaching and learning: a "how to" guide for science academics. Biochem Mol Biol Education 42, 6–14.
47 Zhang L (2007) Promoting critical thinking, and information instruction in a biochemistry course. Issues in Science and Technology Librarianship: 4.
48 Scheffer BK and Rubenfeld MG (2000) A consensus statement on critical thinking in nursing. J Nurs Educ 39, 352–359.
49 Bailin S (2002) Critical thinking and science education. Sci Educ 11, 361–375.
50 The Open University (2015) Digital and Information Literacy.
51 van Gelder T (2005) Teaching critical thinking: some lessons from cognitive science. College Teach 53, 41–48.
52 Ennis RH (2007) Critical thinking and subject specificity: clarification and needed research. Educ Research 18, 4–10.
53 Tiruneh DT, Verburgh A and Elen J (2014) Effectiveness of critical thinking instruction in higher education: a systematic review of intervention studies. High Educ Stud 4, 1–17.
54 Roberts L (2001) Developing experimental design and troubleshooting skills in an advanced biochemistry lab. Biochem Mol Biol Educ 29, 10–15.
55 Holbrook J and Rannikmae M (2009) The meaning of scientific literacy. Int J Environ Sci Educ 4, 275–288.
56 Woodham H, Marbach-Ad G, Downey G, Tomei E and Thompson K (2016) Enhancing scientific literacy in the undergraduate cell biology laboratory classroom. J Microbiol Biol Educ 17, 458–465.
57 Cleaver E, Wills D, Gormally S, Grey D, Johnson C and Rippingale Ju (2017) Connecting research and teaching through curricular and pedagogic design: from theory to practice in disciplinary approaches to connecting the higher education curriculum. In Developing the Higher Education Curriculum: Research-based Education in Practice (Brent C and Dilly F, eds), pp. 145–159. UCL Press, London.
58 Whitworth DE (2016) Recasting a traditional laboratory practical as a “Design-your-own protocol" to teach a universal research skill. Biochem Mol Biol Educ 44, 377–380.
59 Winterman B (2009) Building better biology undergraduates through information literacy integration. Issues in Science and Technology Librarianship, 58.,
60 Ashley J, Jarman F, Varga-Atkins T and Hassan N (2013) Learning Literacies through collaborative enquiry; collaborative enquiry through learning literacies. J Inform Lit 6, 50–70.
61 Chartered Institute of Library and Information Professionals (2012) Information Literacy Skills.
62 American Library Association (2000) Information Literacy Standards for Higher Education.
63 Spiegelberg BD (2014) A focused assignment encouraging deep reading in undergraduate biochemistry. Biochem Mol Biol Educ 42, 1–5.
64 American Library Association (2011) ACRL Presidential Committee on Information Literacy. Technical report, Association of College and Research Libraries, Washington, DC.
65 Booth A (2008) Unpacking your literature search toolbox: on search styles and tactics. Health Inform Lib J 25, 313–317.
66 Rau JL (2004) Searching the literature and selecting the right references. Respir Care 49, 1242–1245.
67 Schönborn KJ and Anderson TR (2010) Bridging the educational research-teaching practice gap: foundations for assessing and developing biochemistry students’ visual literacy. Biochem Mol Biol Educ 38, 347–354.
68 Offerdahl EG, Arneson JB and Byrne N (2017) Lighten the load: scaffolding visual literacy in biochemistry and molecular biology. CBE Life Sci Educ 16, es1.
69 Royal Society of Biology (2018) Accreditation conference: striving for excellence 2018.
70 Power LG (2009) University Students’ perceptions of plagiarism. J High Educ 80, 643–662.
71 Royal Society of Biology. Subject Specific Learning Outcomes. Technical report, Royal Society of Biology, London.
72 Kacpercz K (2014) Non-verbal communication: the importance of listening. Br J Nurs 6, 275–279.
73 Coren E (2013) Why we Need Science Communication: Soapbox Science.
74 Paus C and Russell D (2016) Sociable scholarship: the use of social media in the 21st century academy. J Appli Soc Theory 1, 5–25.
75 Bik HM and Goldstein MC (2013) An introduction to social media for scientists. PLoS Biol 11, e1001535.
76 Miller JD (2013) Scientific literacy: a conceptual and empirical review. Source: Daedalus 112, 29–48.
77 Barclay WR (1976) Science and politics. JAMA 235, 63.
78 Irion R (2015) Science communication: a career where PhDs can make a difference. Mol Biol Cell 26, 591–593.
79 Varner J (2014) Scientific outreach: toward effective public engagement with biological science. Bioscience 64, 333–340.
80 Mercer-Mapstone L and Kuchel L (2015) Teaching scientists to communicate: evidence-based assessment for undergraduate science education. Int J Sci Educ 37, 1613–1638.
81 Richard Tresch Fienberg (2014) Science Communication Skills in a Nutshell.
82 Bridgstock R (2009) The graduate attributes we’ve overlooked: enhancing graduate employability through career management skills. High Educ Res Dev 28, 31–44.
83 Garrison DR (1997) Self-directed learning: toward a comprehensive model. Adult Educ Qly, 18–33.
84 Silen C and Uhlin L (2008) Self-directed learning - A learning issue for students and faculty! Teach High Educ 13, 461–475.
85 Burke D (2009) Strategies for using feedback students bring to higher education. Assess Evaluat High Educ 34, 41–50.
86 Weaver MR (2006) Do students value feedback? Student perceptions of tutors’ written responses. Assess Evaluat High Educ 2, 379–394.
87 Winstone NE and Carless D (2020) Feeding forward: assessment for assessing and developing biochemistry students’ visual literacy. Biochem Mol Biol Educ 38, 347–354.
88 Schönböck KJ and Anderson TR (2010) Bridging the educational research-teaching practice gap: foundations for assessing and developing biochemistry students’ visual literacy. Biochem Mol Biol Educ 38, 347–354.
89 Offerdahl EG, Arneson JB and Byrne N (2017) Lighten the load: scaffolding visual literacy in biochemistry and molecular biology. CBE Life Sci Educ 16, es1.
90 Royal Society of Biology (2018) Accreditation conference: striving for excellence 2018.
90 Winstone N and Millward L (2011) Reframing perceptions of the lecture from challenges to opportunities: embedding active learning and formative assessment into the teaching of large classes. *Psychol Teach Rev* **18**, 31–41.

91 Shute VJ (2008) Focus on formative feedback. *Rev Educ Res* **78**, 153–189.

92 Carless D and Boud D (2018) The development of student feedback literacy: enabling uptake of feedback. *Assess Eval High Educ* **43**, 1315–1325.

93 Biochemical Society (2017) Biochemists in Industry.

94 Zaghloul ARM (2001) Assessment of lab work: a three-domain model; Cognitive, affective, and psychomotor. In *ASEE Annual Conference Proceedings*, pp. 2279–2285.

95 Bloom BS, Engelhart MD, Furst EJ, Hill WH and Krathwohl DR (1956) *Taxonomy of Educational Objectives: Handbook I: Cognitive Domain*. David McKay, New York, NY.

96 Anderson LW and Krathwohl DR (2001) *Learning, Teaching, and Assessing: A Revision of Bloom's Taxonomy of Educational Objectives*, 2nd edn. Addison Wesley Longman, New York, NY.

97 Usluel YK (2007) Can ICT usage make a difference on student teachers’ information literacy self-efficacy. *Libr Inform Sci Res* **29**, 92–102.

98 Slattery M (2013) How Consumer Technology Is Remaking the Workplace.

99 Plunket-Checkemian P (2017) The Workplace of the Future and the role of Technology: Tech the Enabler.

100 Rossi B (2017) Technology is ready to define the future of the workplace.

101 Luu K and Freeman JG (2011) An analysis of the relationship between information and communication technology (ICT) and scientific literacy in Canada and Australia. *Comput Educ* **56**, 1072–1082.

102 American Society for Biochemistry and Molecular Biology. (2017) Accreditation - Curriculum.

103 White HB, Benore MA, Sumter TF, Caldwell BD and Bell E (2013) What skills should students of undergraduate biochemistry and molecular biology programs have upon graduation? *Biochem Mol Biol Educ* **41**, 297–301.

104 Lipchock JM, Gintner PS, Douglas BB, Bird KE and Patrick Loria J (2017) Exploring protein structure and dynamics through a project-oriented biochemistry laboratory module. *Biochem Mol Biol Educ* **45**, 403–410.

105 Marteeel-Parrish AE and Lipchock JM (2018) Preparing chemistry majors for the 21st century through a comprehensive one-semester course focused on professional preparation, contemporary issues, scientific communication, and research skills. *J Chem Educ* **95**, 68–75.

106 Pevzner P and Shamir R (2009) Computing has changed biology – biology education must catch up. *Science* **325**, 541–542.

107 JISC (2008) Joint Information Systems Council, UK. 'Google Generation' is a myth says research.

108 Glynn SM and Denise Muth K (1994) Reading and writing to learn science: achieving scientific literacy. *J Res Sci Teach* **31**, 1057–1073.

109 Ahmad M and Karim AA, Din R and Albakri ISMA (2013) Assessing ICT competencies among postgraduate students based on the 21st Century ICT competency model. *Asian Soc Sci* **9**, 32–39.

110 Earley MA (2014) A synthesis of the literature on research methods education. *Teach High Educ* **19**, 242–253.

111 Luo L (2011) Fusing research into practice: the role of research methods education. *Libr Inform Sci Res* **33**, 191–201.

112 Vinet L and Zhedanov A (2011) A 'missing' family of classical orthogonal polynomials. *J Phys Math Theor* **44**, 8–11.

113 Dodd Xx (2003) *A Guide to Research Ethics*, pp. 1–54. University of Minnesota Center for Bioethics.

114 Richardson S and McMullan M (2007) Research ethics in the UK: what can sociology learn from health? *Sociology* **41**, 1115–1132.

115 Voet JG, Bell E, Boyer R, Boyle J, O'Leary M and Zimmerman JK (2003) Recommended curriculum for a program in biochemistry and molecular biology, 5.

116 Alaimo RJ (2005) Having fun with safety training. *Chem Health Saf* **12**, 16–18.

117 Crockett JM (2011) Laboratory safety for undergraduates. *J Chem Health Saf* **18**, 16–25.

118 Royal Society of Biology and Biochemical Society. *Appendix 1 Subject Specific Guidance - Biochemistry*. Technical report, Royal Society of Biology, London.

119 Mattos C, Johnson M, White H, Sears D, Bailey C and Bell E (2013) Introduction: promoting concept driven teaching strategies in biochemistry and molecular biology. *Biochem Mol Biol Educ* **41**, 287–288.

120 Tansey JT, Baird T, Cox MM, Fox KM, Knight J, Sears D and Bell E (2013) Conceptual foundations and underlying theories for majors in “Biochemistry and Molecular Biology". *Biochem Mol Biol Educ* **41**, 289–296.

121 McDonnell L, Barker MK and Wieman C (2016) Concepts first, jargon second improves student articulation of understanding. *Biochem Mol Biol Educ* **44**, 12–19.

122 Watters DJ and Watters JJ (2007) Approaches to learning by students in the biological sciences: implications for teaching. *Int Jo Sci Educ* **29**, 19–43.

123 Kinchin IM, Cabot LB and Hay DB (2008) Visualising expertise: towards an authentic pedagogy for higher education. *Teach High Educ* **13**, 315–326.
124 Green DA, Loertscher J, Minderhout V and Lewis JE (2017) For want of a better word: unlocking threshold concepts in natural sciences with a key from the humanities? *High Educ Res Dev* **36**, 1401–1417.

125 Johnson RJ (2014) Teaching foundational topics and scientific skills in biochemistry within the conceptual framework of HIV protease. *Biochem Mol Biol Educ* **42**, 299–304.

126 Wright A, Provost J, Roecklein-Canfield JA and Bell E (2013) Essential concepts and underlying theories from physics, chemistry, and mathematics for "biochemistry and molecular biology" majors. *Biochem Mol Biol Educ* **41**, 302–308.

127 Gormally C, Peggy Brickman M, Lutz ML and Lutz M (2012) Developing a test of scientific literacy skills (TOSLS): measuring undergraduates’ evaluation of scientific information and arguments. *CBE Life Sci Educ* **11**, 364–377.

128 American Society for Biochemistry and Molecular Biology. ASBMB Course Content Guidance.

129 Royal Society of Biology (2020) What is Accreditation.

130 The Quality Assurance Agency for Higher Education (2013) *Chapter B1: Programme Design*. Development and Approval. Technical report, The Quality Assurance Agency, London.