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Minireview

MINIREVIEW – Professional Development

A toolbox for digitally enhanced teaching in synthetic biology

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One sentence summary: In this Minireview, a summary of different tools and ressources for digitally enhanced and distance teaching of Synthetic Biology is provided, ranging from virtual mobility over MOOCs to gamification.

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ABSTRACT

The global pandemic of COVID-19 has forced educational provision to suddenly shift to a digital environment all around the globe. During these extraordinary times of teaching and learning both the challenges and the opportunities of embedding technologically enhanced education permanently became evident. Even though reinforced by constraints due to the pandemic, teaching through digital tools increases the portfolio of approaches to reach learning outcomes in general. In order to reap the full benefits, this Minireview displays various initiatives and tools for distance education in the area of Synthetic Biology in higher education while taking into account specific constraints of teaching Synthetic Biology from a distance, such as collaboration, laboratory and practical experiences. The displayed teaching resources can benefit current and future educators and raise awareness about a diversified inventory of teaching formats as a starting point to reflect upon one's own teaching and its further advancement.

Keywords: synthetic biology; higher education; digitally-enhanced teaching; distance education

Definitions

Synthetic Biology "*aims to design and engineer biologically based parts, novel devices and systems—as well as redesigning existing, natural biological systems*" (Kitney and Freemont 2012).

Distance learning takes place in a learning environment in which "*learners and teachers are separated by geographical and/or temporal distance*", while "*a form of mediated learning can be achieved using a combination of technologies*" (Wheeler 2012a).

Digital learning accounts for "*a set of technology-mediated methods that can be applied to support student learning and can include elements of assessment, tutoring and instruction.*", also referred to as technology-enhanced learning or E-learning (Wheeler 2012b).

Emergency Remote Teaching "*is a temporary shift of instructional delivery to an alternate delivery mode due to crisis*

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circumstances. It involves the use of fully remote teaching solutions for instruction or education that would otherwise be delivered face-to-face or as blended or hybrid courses and that will return to that format once the crisis or emergency has abated." (Hodges *et al.* 2020)

Student-centred learning "*is an approach to education, which aims at overcoming some of the problems inherent to more traditional forms of education by focusing on the learner and their needs, rather than being centred around the teacher's input*" (Bologna Follow-Up Group).

INTRODUCTION

Since the onset of the COVID-19 pandemic in the beginning of 2020, Synthetic Biology (SynBio) education—as all study disciplines—is heavily affected by physical distancing constraints. This disruptive change transformed the way education is delivered as there was no alternative but to suddenly switch all teaching and learning from classrooms into the students' homes. Students, teaching and administrative staff had to develop *ad hoc* solutions to bridge teaching and learning during these challenging times. Most higher education institutions did not have—to an extent that allowed them to easily tackle the sudden increased demand—the digital maturity, nor the required ICT infrastructure coverage or appropriate expertise and institutional strategies. Nevertheless, at the same time it became evident that this forced change into a digital environment also bears potential to foster innovative teaching, boost its acceptance among teachers and students and to accelerate the transformation of teaching through digital tools.

In response to the pandemic, educators had to adapt their courses in a short time span with limited availability of individual training and support. In the long term, technical preparedness of teaching staff and educational IT infrastructure are essential parts of the equation towards quality education, but so is training teachers in how to make best pedagogical use of technology-embedded teaching and build confidence among educators to move beyond 'Emergency Remote Teaching'. Not only educators had to learn how to navigate within online teaching platforms but also the learners themselves. Even though one might think about students as 'Digital Natives', the student body's diversity needs to be taken into account. It should not be taken for granted that all students have the necessary skills, access and resources to fully participate in online education.

Particularly teaching SynBio in a virtual environment poses some additional obstacles as this STEM discipline is fundamentally linked to hands-on experience in wet lab exercises and potential research stays that are challenging to convey online. However, shifting into a virtual environment also holds potential. The fast-growing knowledge in the field of SynBio demands for quickly adaptable teaching solutions in the classroom. Even though it is essential that students learn how to adequately handle lab equipment, funding and material for laboratory exercises might be limited. Here, digital alternatives can be used to supplement hands-on practical lessons while easing financial constraints.

SynBio is a field that emerged around the turn of the millennium, bridging various disciplines from molecular biology over computer sciences to chemistry. SynBio aims to break down biological complexity, accumulate knowledge about living systems and standardize it into parts that can be used as a modular toolbox to recombine them in new and predictable biological entities (Cameron, Bashor and Collins 2014). The following characteristics inherent to SynBio have direct implications on how it is taught to students and provide powerful opportunities for its provision in higher education:

- Rapid development: SynBio is progressing at a rapid pace (Meng and Ellis 2020)—so fast that content taught in a SynBio course at this moment can become outdated within a few years. Thus, teaching SynBio requires more frequent updates compared to other fields of research in higher education (Hallinan *et al.* 2019).
- Applicability: SynBio's application potential relates to its power to tackle real-world challenges (Voigt 2020) and can be used in pedagogical concepts like problem-based learning (Kuldell 2007) in order to create meaningfulness and give perspectives on future employment sectors.
- Cross-disciplinary collaboration: SynBio combines a wide spectrum of STEM disciplines but it is also interconnected with entrepreneurship, scientific communication, arts and design, social sciences and ethics (Kuldell 2007). Incorporation of a plurality of perspectives in their education, will allow students to experience working in interdisciplinary teams and synergistically develop ideas.

In order to contribute to sharing good teaching practices for training the next generations of SynBio educators, this Minireview focuses on digital teaching formats within respectively applicable to the field of SynBio. Even though our interest in this topic was triggered by the COVID-19 pandemic's restriction on face-to-face teaching, the impact of innovative teaching goes beyond the scope of this pandemic. By providing an overview of tools for digitally enhanced teaching, the respective strength and shortcomings (Table 1) and corresponding available resources (Tables 2–5)—though by far not an exhaustive collection—we aim to reduce the constraints that are faced in respect to distance teaching of SynBio and at the same time inspire creativity and innovation among STEM educators beyond disciplinary boundaries.

MAIN BODY

Virtual lectures

Virtual lectures are often used to teach fundamental knowledge and can be divided in two types: synchronous and asynchronous. In synchronous lectures, teaching staff delivers lectures live using video conferencing technology. These can additionally be recorded and later made available to students to improve accessibility, while still being considered synchronous. Live delivery allows the lecturers to control and adapt their pace according to the students' needs (Racheva 2018), to use in-time feedback and quizzes about the students' current stage of learning and understanding and to facilitate real-time social interaction e.g. in break-out rooms (Nieuwoudt 2020). Indeed, even before the onset of the pandemic, lecture formats have been shifting away from traditional approaches—characterized by mere knowledge transmission from the lecturer to the students—towards active student engagement. For lectures, approaches that shift part of the students' learning into independent self-study can be found in 'flipping the classroom'—meaning that students have the first contact with learning materials outside of the classroom using lower levels of cognitive skills like acquiring knowledge while the lecture sessions are used for building higher cognitive skills such as analysis and

Table 1. Overview of delivery modes for digitally enhanced teaching and respective strengths and shortcomings.

Delivery mode		Strengths	Shortcomings
Virtual lectures	Synchronous	Teaching fundamental knowledge while remaining interactive	Potentially overstimulating
	Asynchronous	Teaching fundamental knowledge and increased accessibility	Socially isolating and low interactivity
	Virtual mobility	Lowered barriers to engage in mobility programmes, expert lectures from across the globe, language and cultural exchange	Less immersive than physical mobility
MOOCs		Mostly free of charge, flexibility in space, time and choice of content	Dependence on self-management and low interactivity
YouTube playlists and podcasts		Free and easily accessible educational resources	Limited choice and variable quality
Online debates		Peer-to-peer interaction, practice of communication skills	Moderator needed and multitude of online options available without curation of content posted
Social media		Omnipresent, easily accessible and user-friendly	Potential imbalance of work/private life, potential problems in regards to intellectual property laws and privacy and cyberbullying
Virtual labs		Practical and interactive experience based on simulations leading to higher student engagement and acquiring competencies related to laboratory skills	Often advanced computational skills and infrastructure needed
Gamification		Effective motivation and soft skills teaching	Limited choice and relevance for curricula and potential requirement of technical skills on the students' and educators' side
Student competitions		Interdisciplinarity, real life applications, soft skill teaching and acquirement of skills along the full research life cycle	Time and resource consuming

evaluation (Akçayır and Akçayır 2018). This is particularly beneficial for teaching SynBio-related fields which require critical thinking (Winstead and Huang 2019). Within 'Just-in-Time Teaching' the main focus lies on identifying the students' level of understanding by letting the them prepare material and submit assignments before the session, so the teacher can tailor the in-person session towards the most challenging points e.g. to clarify misunderstandings (Marrs and Novak 2004). Pedagogical strategies of this type promote student-centred and active learning by increasing the students' responsibility for their own learning. For more information on how JiTT and flipped classroom approaches can aid teaching—also benefitting virtual lectures—the reader is referred to the work of and Toriz (2019) and Novak *et al.* (1999), respectively. Nonetheless, synchronous lectures have some limitations, such as 'Zoom Hangovers', caused by overstimulation, external distraction and long sessions (Lowenthal *et al.* 2020).

Asynchronous, or on-demand lectures, are lectures which are recorded with the specific intent of being made available online at a later date. Compared to synchronous lectures, asynchronous lectures are less problematic regarding technological reliability and access barriers such as time-zone differences (Lowenthal *et al.* 2020) and allow the students to have more control over how quickly information is presented, decreasing cognitive load and stress (Guo, Li and Han 2018; Nieuwoudt 2020). However, this independence and low interactivity can result in feelings of isolation. Tools such as discussion boards can be key to mitigate emotional attrition, with supportive and reachable instructors (Aloni and Harrington 2018; Lowenthal *et al.* 2020). In the same regard, grading systems are good strategies to promote student engagement (Procko *et al.* 2020). In any case, adequate lecture lengths (preferably under 30 min and strictly under 60 min) should be kept in mind (Guo, Li and Han 2018).

Virtual mobility

International student mobility was heavily affected by international travel restrictions. Consequently, 'Virtual Mobility' suddenly became more inviting. The concept is defined as a '*set of ICT supported activities, organized at institutional level, that realize or facilitate international, collaborative experiences in a context of teaching and/or learning*' (European Commission 2020). It allows students to follow courses at another educational institute than the students' home institute, in other parts of the world in an online mode. Both institutes agree priorly to recognize the course, so it becomes part of the student's curriculum. Virtual Mobility can lower barriers to gain international experience e.g. in regards to financial burden for traveling and living abroad and for students facing health-related and political issues (Buchem *et al.* 2018). Virtual Mobility can also take place in the form of virtual internships in companies, through virtual guest lectures or in physical exchange programs that are complemented with virtual elements. The Erasmus project 'Tea-Camp' funded a 2-year study in which various aspects of Virtual Mobility were studied and assembled the outcomes in one book (Teresevičienė, Volungevičienė and Daukšienė 2011). As a follow-up, the 'Open Virtual Mobility Learning Hub' was designed as a central reference point (Buchem *et al.* 2018).

'Remote Experts' became more accessible to students because of the compelled use of videoconferencing technology. The opportunity to speak directly to authors of scientific research led to increased excitement about otherwise challenging material (Basiliko and Gupta 2015). Also, students themselves can step into the shoes of Remote Experts in initiatives such as 'Skype a Scientist' that matches researchers—even early career researchers from Graduate School onwards—with classrooms around the globe. This way students can practice their

Table 2. Selection of YouTube playlists and podcasts related to SynBio education. In addition to this table, the reader is referred to the article of Dy, Aurand and Friedman (2019) that compiled a comprehensive playlist of SynBio educational YouTube videos.

Name	Type of resource	Knowledge/skills
EMBO/iBiology synthetic biology course	YouTube playlist	Lecture videos about SynBio basics and applications, presented by experts from the field
Synthetic biology one	YouTube channel	Videos providing small online courses explaining simple experiments, presented by Jake Wintermute
Genetics unzipped	Educational podcast	Podcast explaining concepts and examples in the field of genetics
SynBioBeta podcast	Podcast	Podcasts containing interviews with different experts from the SynBio field
Talking Biotech podcast	Podcast	Podcasts containing interviews with different experts in the field of biotechnology

presentation skills and provision of scientific content tailored to a non-expert audience (Skype a Scientist).

Extra advantages of Virtual Mobility are the promotion of second language competency, cultural exchange and mutual understanding among students and researchers across the globe (Al-Samarraie 2019). It can serve as '*an opportunity to reflect and elaborate on renewed models of internationalization at home*' (Coimbra Group 2020). One has to acknowledge that virtual mobility should never aim to fully replace physical mobility because the same levels of support, interaction among students or student–teachers and participant motivation cannot be reached (Buiskool and Hudepohl 2020). A shift to virtual mobility also implies a more elaborate development of online platforms and difficult logistics in terms of planning. In the future, a mixed approach in which virtual mobility is used as preparation; support and follow-up of the physical version is expected to be most beneficial.

Massive open online courses

Massive Open Online Courses (MOOCs) are courses offered on learning platforms that are based on common principles such as democratization of educational offers, video-assisted learning, self-assessment, modularity and short-term education (López Meneses, Vázquez Cano and Mac Fadden 2020). These online courses, which appeared for the first time in 2008, do not have any restriction on the number of enrolled students and are free of charge to everyone, although fees must usually be paid to receive a recognizable certificate. MOOCs have the potential to diversify the higher educational landscape, by providing easily-scalable, informal and student-centred alternatives to traditional programs, as MOOCs give students more autonomy to shape their individual learning paths and expand the curriculum further than their traditional education programs (Lambert 2020; Blum-Smith, Yurkofsky and Brennan 2021; Julia, Peter and Marco 2021). One of the biggest advantages of MOOCs is the great variety of topics directly accessible to learners.

Nevertheless, MOOCs show several weaknesses that limit their expansion: high dropout rates, lack of feedback, low interaction, absence of reliable examinations and difficulty to assemble an individual curriculum out of the wide range of MOOCs available as well as limited recognition of the competencies acquired through MOOCs by formal institutions (López Meneses, Vázquez Cano and Mac Fadden 2020; Reparaz, Aznárez-Sanado and Mendoza 2020; Zhu, Bonk and Doo 2020; Pickard, Shah and De Simone 2018). MOOCs can introduce SynBio to students studying related programs, such as biochemistry or computer sciences, which do not necessarily include SynBio in their curricula. The MOOC 'Principles of Synthetic Biology', developed by MIT and provided on EdX, gives an overview on the engineering approach of this discipline (Anderson *et al.* 2019). In the same way that MOOCs can be used to introduce learners from related disciplines SynBio, they can also be used to expand the knowledge of SynBio students into areas related to the interdisciplinarity of SynBio, such as programming or bioethics. For example, the MOOC 'Engineering Life: Synbio, Bioethics & Public Policy', developed by Johns Hopkins University and provided on Coursera, gives an overview on the ethical and legal implications of several SynBio applications (Mathews 2021).

During the pandemic not only have students turned towards MOOCs for knowledge and credits, also teachers have made use of them as inspiration to create their own online courses. The rise of MOOCs during the pandemic is reflected in a three-times increase of subscribed learners between 2019 and 2020, compared to the previous term. Although during the pandemic MOOCs usage has increased worldwide, the question remains open whether MOOCs will maintain this trend after face-to-face education can be fully restored.

YouTube playlists and podcasts

While through MOOCs credits can be awarded to be used in formal studies, there is a vast number of informal educational resources available on the web, such as YouTube videos or podcasts. Students can easily consult these free resources to support their learning process and teachers can use them as inspiration or supporting material. Even though they provide freedom to students, their quality may be irregular or untrustworthy (Drew 2017).

Besides being a passive source of information, YouTube—the biggest open-access repository of videos—can be actively integrated in education, with students publishing videos for projects and teachers creating contents that their students and other interested parties can follow (Almobarraz 2018; Curran *et al.* 2020; Ssentamu *et al.* 2020). However, awareness about the usefulness of YouTube and similar platforms for teaching still needs to be encouraged among education professionals. YouTube offers a range of resources for SynBio as exemplified in Table 2. In addition, the reader is referred to the article of Dy, Aurand and Friedman (2019) that compiled a comprehensive playlist of SynBio educational videos found on YouTube.

Starting with the exchange of private audio files, podcasts have evolved into a free and open format to distribute information. Podcasts can be used in different ways: as substitutional material (providing essential course content), as supplemental material (providing reviewed course material), or as integrated material (providing non-essential extra material). The

Table 3. Overview of resources for online debates and discussions.

Online forum	Type of platform	Knowledge/skills	url
IndieBiotech.com	Discussion forum	Forum for discussion about democratized biotechnology	https://www.indiebiotech.com/
DIYBio	Mailing list	Finding tips and tricks to perform biology/biotechnology at home and open for ethical discussion	https://groups.google.com/g/diybio?pli=1
Biology Online Forum	Discussion forum	World's most comprehensive database of biology terms and topics	https://forum.biologyonline.com/
ResearchGate	Social media network	Social media network to share articles and opinions and large Q&A section covering technical support	https://www.researchgate.net
Biology.StackExchange	Discussion forum	Q&A site for biology researchers and academics and students	https://biology.stackexchange.com/
SynBio.StackExchange	Discussion forum	Q&A site for synthetic biology researchers and academics and students	[upcoming] https://area51.stackexchange.com/proposals/125068/synthetic-biology?phase=commitment&conf=1

use of podcasts as integrational material is the rarest application but at the same time it has the highest potential (Connor *et al.* 2020). The design of podcasts is of particular importance to provide significant learning experiences. Podcasts can benefit from a high use of structural guidance techniques to continuously remind the audience of the message context, as well as brief and intense episodes or an informal style based on humour (Drew 2017; König 2020). For SynBio podcasts, as for podcasts in general, it is common to have several speakers either in the form of interviews or round table discussions. Podcasts centred around SynBio are not abundant, and the content of the ones available might be too advanced for students not yet familiar with the subject. Nonetheless, podcasts can be of great help for further insight into specific topics or as material about the intersections of SynBio with other disciplines, such as business or ethics. A selection of SynBio YouTube playlists and podcasts can be found in Table 2.

Online debates and discussions

Achieving students' full engagement in the online learning environment requires high interactivity with the learning materials, but also an elaborate social learning network. Online debates and discussions are a good start since they increase peer-to-peer interaction, which provides opportunities to practice communication skills and increases student interest by providing platforms for dialogue. During the discussions, the teacher is in the role of a moderator that oversees the content and should be aware of the abundance of online fora without curation of the content posted. A teachers' guide on the practical aspects how to moderate online discussions was written by Feenberg, Xin and Glass (2002). Online tools—such as the online debate website 'Kialo Edu' (Kialo Edu)—are designed to help moderate these discussions in an online classroom setting.

Zooming in on communities more specifically dedicated to SynBio, one encounters among other *DIYBio.org* (Table 3), a global project with its own general ethical framework, open-source mindset and, most importantly, supra-national networks to meet other junior and amateur SynBio scientists online. These discussion platforms provide students with the opportunity of joining SynBio communities outside formal education; thereby, allowing them to engage with laypersons from the general public from early on in their scientific careers. Other examples of discussion fora and networks are given in Table 3.

Social media

Through social media platforms, learners and educators can interact with each other online. One of the first forms of social media were blogs, which can be defined as an online publishing format characterized by a collection of links, news, or opinions with an informal and subjective style and appear in inverse chronological order (Barujel 2005). The use of blogs in higher education (termed 'Edublogs') has been proposed since the early 2000s (Cabrera 2019). Educators can create blogs which can be accessed at any moment and respond to students' questions and comments. Furthermore, students can be encouraged to create blogs themselves, where they can structure and publish their gained scientific insights, improving skills to acquire and organize knowledge, aiding to developing life-long learning competencies.

The spread of mobile technologies and the appearance of other social media formats provide alternatives to blogs. The advantages of mobile technologies are obvious: the big social media players such as Facebook and Twitter provide infrastructure, outreach and the potential for student engagement with new forms of delivery (Cann 2015). Even more, 'Microblog' platforms (any online platform where messages are restricted to 140–200 characters) encourage participation in socio-scientific topics, developing argumentation skills among students (Shaw, Walker and Kafai 2020). Compared to blogs, the accessibility of these mobile social media is much more direct, and the notification systems allow for more dynamic sharing of knowledge (Chawinga 2017). A study across a variety of disciplines showed that students are comfortable with frequently using social media in their education and that it supports deep learning (Samuels-Peretz *et al.* 2017).

Inside the microbiology field, the 'Adopt a Bacterium' project is one example, promoting an interactive teaching experience using Facebook as a platform for shared and supervised discussions (Piantola *et al.* 2018). Also, on LinkedIn, several open SynBio groups are found, such as the 'iGEM', 'CRISPR and Gene Editing Tools', 'DIYbio' groups. The hashtag #synbio on Twitter guides students towards researchers and their publications in bitesize bits. More than ever, science communication and distribution of research output is changing its trajectory towards social media, urging teachers to include or consult them when updating the curriculum. More information on how social media impacted microbiology dissemination can be found in the communication by Al *et al.* (2021).

Table 4. Overview of resources for virtual lab experiments.

Virtual lab	Knowledge/Skills	url	Ref
Serial Cloner, Benchling	Virtual PCR and cloning	*http://serialbasics.free.fr/Serial_Cloner.html*, *https://benchling.com/signin/welcome*	Benchling; Serial Cloner; Fellermann *et al.* (2018)
Virtual Enzymology	Enzyme kinetics	*https://github.com/vqf/kinetics*	Quesada (2020)
GelBox	Gel electrophoresis	*http://douglaslab.org/gelbox/*	Gingold and Douglas (2018)
Aipotu	Links genetics, biochemistry and molecular biology with evolution	*http://en.bio-soft.net/biocai/aipotu.html*	Katsaros and Stasinakis (2020)
BioNetwork Virtual Microscope	Interactive virtual 3D microscope	*http://www.ncbionetwork.org/iet/microscope/*	NCBioNetwork
Augment app	3D protein structure in Augmented Reality	*https://moleculareweb.epfl.ch/*	Hoog *et al.* (2020)
Labster	SynBio routine from building the genetic circuit, the cloning thereof through plasmid extraction and transformation	*https://www.labster.com/simulations/synthetic-biology/*	Labster
COVID Moonshot	Modelling of potential inhibitors targeting the main protease of the SARS-CoV-2 virus	*https://covid.postera.ai/covid*	Brandt and Novak (2021)

Yet, one should be aware of the associated challenges of using social media for educational purposes. The expectation of short response times and the omnipresent nature of this medium often leads to imbalances in the work/private life separation, which in turn causes stress and anxiety for teaching staff and students (Lepp, Barkley and Karpinski 2014). When using social media, one also needs to be aware of problems in regard to intellectual property laws, privacy, cyberbullying and digital and information illiteracy such as for identifying misinformation. Furthermore, the limited character space and volatility of social media do not leave a lot of room for nuances. Given the complexity of SynBio issues, students tend to be drawn to their peers' perspectives and thereby reinforcing their own biases (Shaw, Walker and Kafai 2020). Nonetheless, social media cannot be ignored for its impact on our every day's private and professional lives and therefore should be used adequately to contribute to active learning. Evidence-based recommendations and guidelines for including social media in one's teaching are provided by Greenhow and Galvin (2020).

Wet lab simulators and virtual labs

Particularly in applied sciences, the perceived value of distance learning suffers from a negative stereotype (Matias and Springs 2020). This originates mainly from the need to acquire a hands-on foundation (including skills involved in investigation, experimentation and evidence evaluation). Molecular biology students stated the lack of performing hands-on lab techniques during the pandemic as one of the major barriers to their learning (Hsu and Rowland-Goldsmith 2021). The fast switch from in-person to online teaching often led to the use of lab videos of teachers performing experiments or animations without any interactive aspects. For a vast database of these videos, the reader is referred to 'JoVE' or 'LabXchange' (JoVE; LabXchange). Additionally, free videos can also be consulted on YouTube. By using demonstration videos, instead of physically performing the experiments, the focus shifts towards the conceptual understanding of a technique and data analysis. Yet, students still reported having troubles grasping the underlying concepts. This indicates the importance of the exploratory and creative aspects of actively performing lab experiments.

In SynBio, molecular procedures such as cloning can be easily simulated with computer resources such as in PCR simulators ('Virtual PCR Simulator', Table 4) and even whole DNA assembly environments ('Benchling' or 'Serial Cloner', Table 4). These simulators provide a conceptual space to rehearse prior theoretical knowledge, without requiring expensive reagents and equipment. Together with a multitude of sequence repositories such as the 'NCBI Database' or 'Addgene', these simulators facilitate the design of molecular constructs, sequence analysis, PCR primer design and other skills which are all key learning objectives in molecular biology. Yet, the benefit of simulators goes beyond the design stage, nicely illustrated by the availability of various resources for virtual lab experiments (Table 4).

Interactive simulation tools provide a valuable alternative to the analogue lab experiments, with a higher student engagement compared to lab animations or videos (Diwakar *et al.* 2016; Allen and Barker 2021). In the virtual environment, students can perform individual lab experiments from PCR over gel electrophoresis to microscopy or engage in performing a whole SynBio routine from building a genetic circuit to transformation by using e.g. 'Labster' (Table 4). Before the pandemic, lab simulation-based practical training in higher education was rarely used to replace real-life exercises. From an industrial biopharmaceutical perspective, it was found that these virtual trainings could vastly substitute real-life trainings (Wismer *et al.* 2021). Even if a few lab simulations require advanced computational skills and infrastructure it is conceivable that virtual labs might play a more central role in the future of SynBio education, even after the pandemic.

Preferably, lab experiments—online or in-person—result in real-world significance, something that appeared crucial for the motivation of students (Van Heuvelen *et al.* 2020). The most relevant example of an online practical exercise with a reality-grounded outcome, stems from the crowdsourced COVID-19 'Moonshot' project (Table 4). Here, students apply their scientific knowledge and creativity in search for inhibitors targeting the main protease of the SARS-CoV-2 virus (Brandt and Novak 2021). All results are posted in a communal database and automatically scored. The highest scoring candidates are synthesized and tested as an actual treatment for SARS-CoV-2, providing the societal relevance to the project.

Table 5. Fully online educational games with elements useful for SynBio teaching.

Name	Knowledge/skills	url	Ref
Geniventure	Virtual game environment teaching basic genetic concepts through puzzle-like challenges	*https://geniventure.concord.org*	Henderson *et al.* (2020)
Mission Biotech	Virtual game environment in which the player represents a scientist studying an emerging epidemic	*http://www.virtualheroes.biz/MissionBiotech*	Eastwood and Sadler (2013)
Hero.Coli	First-person simulator of a bacteria incorporating genetic elements to gain new properties	*http://herocoli.com*	Goujet (2018)
SynMod	Game for mobile devices, the player learns about amino acids and their properties and aims to use this knowledge to develop new antibiotics	*https://www.biofaction.com/portfolio/synmod-game*	Schmidt, Radchuk and Meinhart (2014)
FoldIt	Multiplayer competitive game that simulates protein folding	*https://fold.it*	Cooper *et al.* (2010)
Nanocrafter	Virtual game environment in which the learner can simulate the assembly of DNA fragments to construct novel genetic devices	*Unavailable*	Barone *et al.* (2015)

Gamification

'Gamification' refers to the use of game elements in non-game environments. Using gaming strategies in teaching can result in higher grades, higher engagement and student participation and the development of soft skills such as leadership, reflection on scientific values and self-discipline (Toriz 2019). By design, games promote curiosity and exploration, and provide feedback for tasks. Effort is rewarded through public praise, such as leader boards and congratulatory messages, while mistakes are assimilated through 'fun failure', which is non-threatening, and thus does not induce anxiety but invites additional exploration (Morris *et al.* 2013).

In addition to the benefits for students' learning, smart game design can be used to solve real scientific problems. 'FoldIt' is a perfect example in this regard (Table 5). The skills of players were harnessed to predict the 3D structure of folded proteins; with top players succeeding at a greater degree of accuracy than contemporary software. This demonstrates the potential of SynBio games to push the scientific frontier (Cooper *et al.* 2010). Relevant games in the field of SynBio are compiled in Table 5, which are considered well suited for integration in distance learning.

However, SynBio games are not limited to completely virtual game environments. Collaboration with other students can be enhanced by SynBio-related escape room games that can be executed online while communicating through video conferencing technology (Alonso and Schroeder 2020). Furthermore, some games can be played virtually but rely on real-time, physically occurring molecular or organismic biological processes, termed 'Biotic Games'. For example, at the organism level, *Euglena* (Gerber, Kim and Riedel-Kruse 2016) and *Paramecium* (Riedel-Kruse *et al.* 2011) responding to external stimuli applied by players can be used in minigames like Pong, Pac-man and soccer. In other games such as 'Mould Rush' players scan the growth of microbial cultures and score points for identifying colonies (Pataran *et al.* 2020).

Gamification as an educational tool is not without limitations. A lack of technical skills both on the educators' or students' side can hinder participation. Furthermore, the narrow scope of individual games and the limited number of games available often leads to them not necessarily aligning with course milestones, or only covering certain parts of the desired learning. Therefore, proper thought and prior planning should be placed to guarantee that games are appropriate to the study topic at hand (Sánchez-Mena and Martí-Parreño 2017).

Student competitions

SynBio competitions, such as iGEM or BIOMOD, allow teams of students to present ideas which they have designed, built and tested. These ideas should be directed to solve real-world problems and should involve the design of organisms (iGEM) or molecules (BIOMOD) (Kelwick *et al.* 2015; Schmitt *et al.* 2020). However, the area of responsibility goes beyond pure research planning and execution: Participants are asked to also cover research management such as collecting funds from sponsors, managing their budget, researching societal implications as well as creating deliverables for the competition such as websites or posters. Due to the pandemic, BIOMOD 2020 was cancelled while iGEM 2020 was taken fully online and requirements and goals were adjusted to allow the possibility to win prizes for those teams that could not access laboratories. iGEM 2020 showed that a worldwide student competition taking place entirely online is a feasible task. Besides the main SynBio competitions, students can also work on SynBio-related projects in competitions with a broader target group, such as the BioBased Innovation Student Challenge Europe (TKI-BBE 2021).

Student competitions can offer students motivation to apply their knowledge to real-life situations, gaining new SynBio and interdisciplinary skills in the process (Gadola and Chindamo 2019; Herrera-Limones *et al.* 2020). Furthermore, the big scope of these competitions requires team effort from students rather than individual work, fomenting the development of interpersonal and teamworking skills (Schuster, Davol and Mello 2006). However, educators should be aware of the—depending on the scope of the competition—time and resource consuming character of student competitions. Another type of student competitions are hackathons in which a team, often interdisciplinary, seeks to develop a solution or an algorithm to a real and previously defined problem in a limited amount of time, ranging from several hours to multiple days. SynBio has the potential to provide stimulating problems for hackathons in educational settings, in which students can develop their programming skills and understanding of biology in interdisciplinary groups (Cambridge University; Horton *et al.* 2018; Gama *et al.* 2019; ELIXIR 2021). Based on previous hackathon experiences, a team of researchers developed guidelines on how to organize and manage Bio-Hackathons which can serve educators that aim to implement hackathons at their institutions or in their courses (Garcia *et al.* 2020).

CONCLUSION

The COVID-19 pandemic has led to temporary physical closure of higher education institutions and forced teachers and students into a rather drastic and global switch from in-person teaching to 'Emergency Remote Teaching'. Even though remarkable responses have been made, the abrupt switch to digital education was rather a solution in the moment of crisis than based on proper long-term implemented technical, professional and pedagogical strategies. With this Minireview we provide a diversified toolbox (Table 1) with explicit examples for educators to easily consult when designing and conducting their higher education courses in an online environment. Above, we have showcased a range of SynBio-specific but also a variety of SynBio-linked resources as SynBio is inherently associated with interdisciplinarity. Consequently, not only SynBio teachers can profit from this toolbox but due to its transferability also educators from other related disciplines that are looking for inspiration can benefit from it.

Social interactions between students are crucial for the learning process, creating a sense of belonging to a college cohort and expanding interpersonal soft skills. Learning full-time online—without a physical space to interact—can have negative consequences for students' physical and emotional well-being such as feelings of isolation. Formats like student competitions can largely support student community-building. However, most of the interactions in a digital setting are rather formal, whereas informal contacts like joint lunch breaks are more difficult to institutionalize. Even though 'Virtual Mobility' can be seen as an alternative to overcome the travel restrictions, since it addresses cultural awareness and intercultural collaboration to a certain extent, it is evidently distinct from physical mobility in which the student immerses in a culturally different environment. Another shortcoming of teaching SynBio online, is the current inability to perform wet lab exercises. Virtual labs can partially be used as substitute, but lack the real proper handling of laboratory equipment and immediate trouble solving. These situations highlight the challenges of virtual environments when it comes to human connection, networking and hands-on experience.

Another point of attention is the sustainability of online resources for teaching. Digital resources need to be maintained and updated to ensure accessibility and state-of-the-art scientific material. Depending on the tool used, educators need to pay attention to identifying scientifically sound resources. Oppositely, this can also provide opportunities to train students' information and data literacy. Generally, teaching online asks for considerations about the risks of cyberattacks, data misuse and privacy protection—especially when teachers and students are required to sign up for accessing a platform using their own, or their university's information.

In any case, one should bear in mind that the student population is diverse and students can face problems when it comes to private and quiet spaces to work remotely from home, lacking technical equipment or limited internet connection as well as limited digital literacy. Furthermore, barriers encountered by students with disabilities and impairments need to be taken into account from the beginning e.g. by using the guidelines of 'Universal Design for Learning' (Dell 2015; Rogers-Shaw, Carr-Chellman and Choi 2018). This said, it is crucial that ICT, other support structures and educators are capable to provide a safety net for all learners to counteract inequalities and the digital divide.

The delivery modes and respective resources displayed in this Minireview can provide starting points for a fruitful teaching and learning experience. However, teachers should bear in mind that digital tools and resources are only a medium for delivering information but do not *per se* cause effective and student-centred teaching. Ideally, modern evidence-based pedagogical approaches and digital teaching tools blend together and are complementary to reach the intended beneficiaries. Especially in the digital environment teachers need to adapt their teaching style and carefully design their teaching units. This said, educators are encouraged to consult their institutions' pedagogical assistance and benefit from MOOCs for teachers' professional development themselves e.g. 'Blended and Online Learning Design' (developed by UCL and provided on FutureLearn) and other published materials (Bruggeman *et al.* 2021; Mahmood 2021; Sharp *et al.* 2021). In the sense of student-centred learning and teaching, students can become co-creators of their own learning and generate valuable online teaching content themselves while strengthening the student-staff partnership.

Even though there is no 'One-Size-Fits-All' solution, this review aims to contribute to peer-learning among educators. As SynBio itself, the teaching landscape is facing a rapid development and continuous improvement in which also digital tools find their place. Digital teaching solutions used synergistically together with appropriate teaching methodology have the potential to make best use of flexibility—in time, place and content—for learners and educators to reach desired learning outcomes. Therefore, educators—from early career researcher that are teaching their first courses towards senior academics with multiple decades of teaching experience—should use the lessons learnt from crisis-driven experimentations and innovations as an opportunity to reflect on and reimagine their own practices to teaching post-COVID19–just like SynBio typically relies on a Design-Build-Test-Learn cycle to constantly readjust and improve.

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