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Article

eLearning and eMaking: 3D Printing Blurring the Digital and the Physical

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Abstract: This article considers the potential of 3D printing as an eLearning tool for design education and the role of eMaking in bringing together the virtual and the physical in the design studio. eLearning has matured from the basics of lecture capture into sophisticated, interactive learning activities for students. At the same time, laptops and internet enabled phones have made computer-based learning mobile, invading classroom learning, changing communication between students, enabling on the spot research, and making the recording of ideas and activities easier. The barriers between online and offline are becoming blurred in a combined digital and physical learning environment. Three-dimensional printing is part of this unification and can be an empowering learning tool for students, changing their relationship with the virtual and the physical, allowing them to take ideas and thinking from screen to reality and back again in an iterative, connected process, however, from an eLearning point of view it is, more importantly, a transformative technology with the potential to change the relationship of the learner to their learning and the scope and nature of their work. Examples from Griffith Product Design student learning illustrate the potential of eMaking to enhance combined learning in a digital age.

Keywords: 3D printing; eLearning; digital fabrication; eMaking; student centred learning

1. Introduction

This article is about the broadening scope of eLearning. In particular it is about how eMaking, based on 3D printing as part of an eLearning strategy, has implications and opportunities for learning and teaching that go far beyond the documented benefits of conventional digital fabrication technologies in design student learning, such as demonstrated through the use of computer numerically controlled routers in studio learning [1]. Web 2.0 has changed learning, and this article provides a tangible example-through 3D printing-of how it is opening up new learning opportunities that change the students' perspectives and supports significant learning.

The article is divided into three sections.

- The first deals with the straightforward, observable improvement in student work that has occurred with the introduction of 3D printing technology into the teaching studio.
- The second addresses the changing relationship that is observable between the students and the lecturers when the broader implications of 3D printing as part of eLearning are taken into account.
- The third gives examples of how the technology and eLearning are linking the student to a much bigger sense of the world, their responsibilities, ethics, *etc.* and are changing practice.

The examples given are from the first year Product Design studio at Griffith University (except for the heart project, which is from a Masters student at Griffith) and are based on evidence of changing practice over the last four years.

2. The Introduction of 3D Printing Technology into the Teaching Studio

Student centred learning and the importance of empowerment, as discussed in Weimer's seminal work on changing the balance of power in the classroom in higher education [2], is at the heart of bringing 3D printing into the Product Design studio. Fundamentally, 3D printing creates a direct link between a 3D-computer-based model and the formation of an accurate object from that model. Before anything else is considered, the direct linking of object making to computer based modelling immediately changes the relationship of the student to making.

For anyone unfamiliar with the technology, 3D printing developed from rapid prototyping into a range of processes technically known as additive manufacturing as they all build objects up in layers and are not dependent on preformed moulds or tooling. The desktop fused deposition modeller (FDM) in Figure 1 is the most basic form of the technology. It extrudes an engineering grade polymer, acrylonitrile butadiene styrene at approximately 0.2 mm suitable for practical use. The polymer is heated to over 220 degrees Celsius (with the platform is heated to around 100 degrees Celsius) so that each successive layer adheres to the one before. Although it is a slow process, students are engaged by it. As an example, Figure 2 shows a speaker housing that a first year student at Griffith University designed, modelled, and printed on a desktop FDM, outside of set assignment work, within weeks of learning the basics of the technology.

Figure 1. 'Up' desktop 3D Printer.

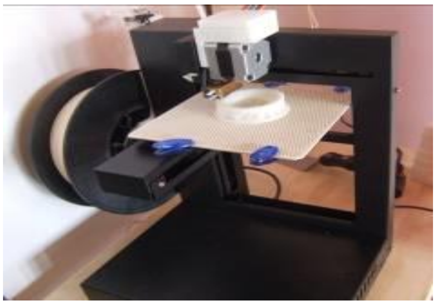
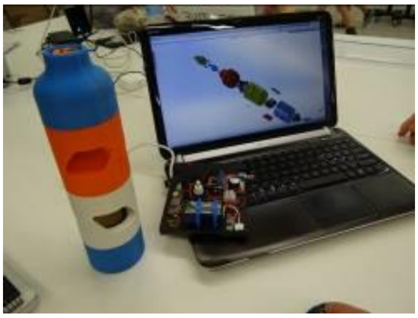
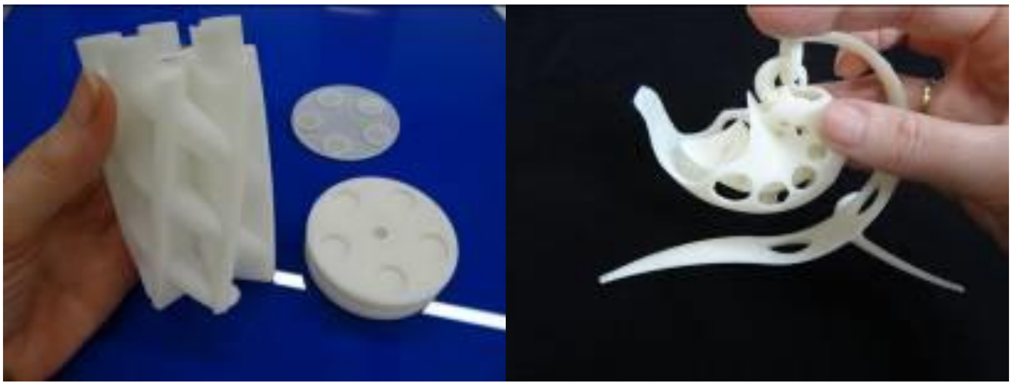


Figure 2. Housing for functional speaker 3D printed by first year student, Troy Baverstock.



Learning by making has a long established history in design education as products have to be taken beyond concepts, through an iterative process of testing and development [3] into a reality that can withstand the rigours of functional, as well as aesthetic roles once they are commercially manufactured. However, in recent years, workshop practice in higher education has been losing traction both with faculty because of high running costs and increased liabilities [4], and with the students themselves because of a lack of enthusiasm for spending time in the workshop environment. For a generation that has predominantly been brought up immersed in a virtual world, where, in a single internet minute, there are around 609,800 gigabytes of data transferred, 204 million emails sent, 2.5 million searches undertaken, 3000 photographs uploaded, and 100,000 tweets [5], physical workshops are likely to be more alien environments than for previous generations. For Product Design education, the corresponding rise in 3D-computer-based modelling to its current level of sophistication has added to that disconnect, with students drawn to the more familiar workspace. As 3D-computer-modelling has developed, the proportion of time the student spends in the virtual environment has increased, taking time away from the studio and from practical workshops. By linking a form of physical making directly to the 3D virtual environment, 3D printing builds on that computer confidence, rather than works outside of it. This has been observed in examples of practice at Griffith University. There is a contrast between first year visual, physical product design models built in modelling foam in the workshop (previously the only option for creating quick sketch models for design development for ergonomics for example), and the complex objects created with 3D printing, such as those shown in Figure 3, created by first year students in 2013. Three-dimensional printing enables the students to realize the sophisticated models they imagine, based on their expertise in 3D computer-based modelling, not based on their skills in the traditional workshop.

Figure 3. Examples of first year sketch models 3D printed in class that would be too difficult to sculpt in conventional model making foam (**a**) Matt Deshon (**b**) Dave Haggerty.



Whilst this could be expected to further distance students from conventional workshop practice, this has not been the case [6]. Reconnected to making, and with confidence in their ability to create physical objects from concepts, students are then able to be bridged into workshop practice through activities such as jig making, which engage them critically, rather than through conventional introductory workshop skills.

In the design studio, 3D printing fundamentally reconnects students to objects and the reality of their work, which is topical as one of the most significant issues for design in higher education over the last ten years has been the breakdown of traditional studio practice [7] and the fragmentation of process. Design is an iterative process [8] where students develop concepts through research, reflection, drawing, studio model making, and workshop prototyping. Workshops have been integral to design learning, as without hands-on experimentation as part of design development it is difficult for students to develop the understanding of material characteristics and behaviours necessary to translate concepts into reality. Although there are still exceptions, such as in Product Design studio practice at Stanford [9], modularisation of the curriculum has tended to separate out workshop and studio. In addition, since the late 1990s, computer based 3D modelling software has grown in sophistication to a point where virtual models can be assigned material properties and tested. Concepts can, to an extent, be explored on a design level during 3D computer based modelling, and the opportunities afforded by techniques, such as generative modelling influence design thinking. Computer aided design (CAD) should therefore no longer be considered a documentation tool added to the end of design process, but rather be viewed as part of design development and integrated into it.

At Griffith University, in the first year design studio, a new workspace has been developed over the last three years that was formerly introduced in 2013, based on the idea of eMaking. The aim has been to reconnect studio, CAD and workshop but also to design a workspace that is based on designing now, as opposed to historical practice, with group work and Internet based communication essential and constant access to resources on the web and online learning content as a requirement.

Figure 4. Combining studio practice, online research, 3D-computer-based learning and digital fabrication through 3D printing for iterative design process, and group work for design students.

Ramsden states, "A focus on collaborative, supportive and purposeful leadership for teaching is associated with a culture of strong teamwork and student-focused approaches" [10]. By creating eMaking studio facilities as digital hubs, students can discuss and develop ideas on screen and through the physicality of form and structure more easily. By creating table space and floor space around the idea of a 'digital pod' (see first year Product Design students at work in the studio in Figure 4), students can work seamlessly between drawing, sketch modelling, online research, computer modelling, and digital fabrication, in a learning cycle that moves their design thinking forward with more self determination. This new form of digital design studio places the student very much in the centre of their own learning with the facilities to work iteratively both on their own designs and in groups.

3. Changing the Student's Perspective through 3D Printing as Part of an eLearning Strategy

3.1. Changing Product Design Student/Lecturer Relationships

Fundamental to this independence through changed studio practice is Ramsden's research in education where he states that "an information-transmission, teacher-focused approach to teaching on the part of a teacher is associated with a surface approach to learning on the part of their students, while a conceptual change and development, student focused approach to teaching is associated with deep learning" [10]. Central to student centred learning is a shift of the balance of power within the learning experience from the lecturer to the student [2] and that has occurred in this case partly because of the unforeseen broader impact of 3D printing on design practice and product and the Internet as a research and communication tool. Formerly information coming into the design studio predominantly came from the lecturer and the resources and research direction the lecturer provided. As resources were chosen and developed by the lecturer, they were familiar to–and endorsed by–that lecturer. Student questions could therefore be anticipated, and it is likely too that most questions would be similar in any repeat taught sessions. Most design lecturers bring, to their role, direct experience of industry practice on which they draw for their teaching. Since the industrial revolution, mass production practices have essentially been refined rather than replaced. Experience in one technology generally informs practice in others, and the underlying principles for mass production have applied across disciplines. This is not the case with 3D printing. There are constraints and opportunities, as there are with all other production processes, but, for example, removing the upfront cost of mould making makes it possible to create individual designs as a 'one-off' in materials not previously possible. Rules for creating forms and structures are different and the applications are breaking the traditional discipline boundaries, opening new directions for 3D designers to work in. In the majority of cases, lecturers are striving for professional development in these technologies alongside student learning. Credible 3D printing book publications are few at this stage and the rapid pace of development means that Internet resources from credible sources are currently more reliable for accurate up to date information. The breadth of applications affected by 3D printing is so wide–from architecture to medical-that the lecturer would struggle to maintain a sense of developments on their own. It is in therefore in lecturers' interests to encourage students to maintain a watching brief on developments and report them back to the class, and this has led to a change in the relationship between students and lecturers, where the student is as likely–more so as a cohort–to be bringing new information on the spread of the technology to the classroom as the lecturer. This being the case, the information cannot possibly be pre-vetted by the lecturer and inevitably there are conflicting reports, information and opinions. These have to be discussed first hand in class and that puts the learning realistically in the control of the cohort, bringing the lecturer along with it. The student is then likely to form the stronger sense of self-education important for lifelong learning and consider the lecturer as a mentor rather than a leader.

Design graduates will be working on projects that by their very definition are new each time. Creating proactive learners who base their work on researched information and considered opinions is essential for the discipline. Introducing 3D printing into the studio significantly contributes to this (at this time) if the lecturer fosters a broad eLearning approach, encouraging online research, interaction, and discussion. For the lecturer, abandoning 'flight mode' for phones, iPads, and laptops in favour of actively encouraging students to look up every reference in real time during a lecture or discussion allowing time for students to find related references and using live web references over downloaded images and information does require an additional level of confidence and a willingness to allow preplanning to be derailed by a student challenge. However, an advantage of this approach is that it means the lecturer can be as stimulated by the learning as the student, with the relationship between students and lecturers altered by the shared experience (Figure 5 shows a first year student creating her own podcast with the lecturer rather than relying on a premade generic podcast).

Figure 5. First year Product Design student creating her own podcast based on a demonstration using her own project rather than relying on generic podcasts uploaded by the lecturers.

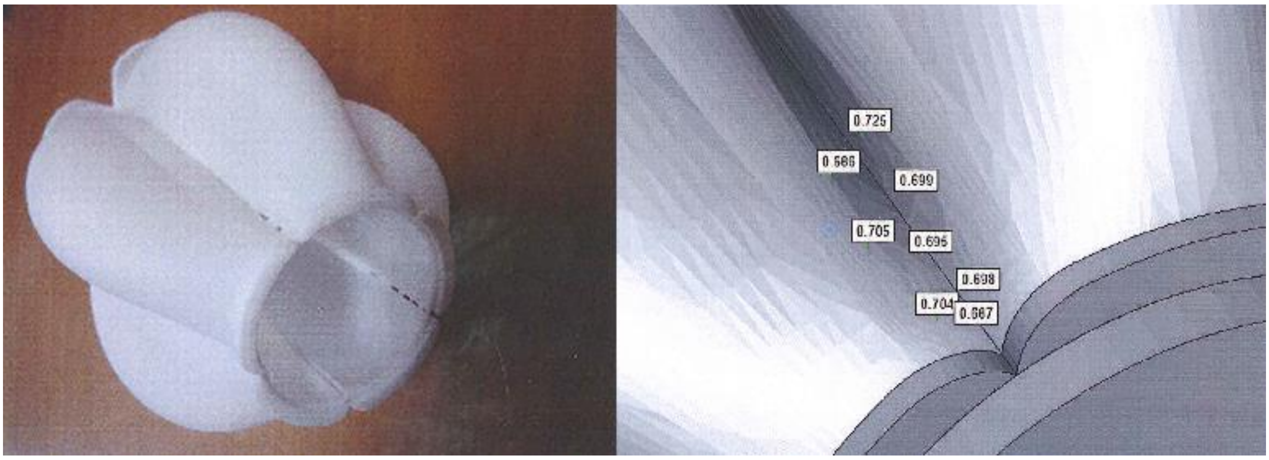
In his book, Making Teaching Work [11], Race identifies a growing disconnect in higher education between students and lecturers as a contributory factor to student attrition and suggests lecturer morale is adversely affected for the same reason. The shared experience of exploring rapidly changing 3D printing developments on the Internet that were new to the lecturers and the students at Griffith was shown to reconnect the two groups on a personal level and an enthusiasm for eLearning as part of a blended learning strategy contributed to the development of a version of a 'flipped classroom' approach [12], where students researched the topic outside the classroom and used the time within the classrooms for synthesis, rather than lecturer led dissemination. Courses formatively developed in this way, by lecturers in conjunction with students, contribute to a shared approach to learning that can be positive for all concerned. Educational research into relinquishing control in the classroom has shown that there are benefits from the unpredictability of the experience, for example in courses based on student run simulations [13], that contribute to a deep learning experience that were mirrored in this study. Evidence of this includes student-generated projects that were initiated after the assignments were submitted.

3.2. eLearning in a Global Digital World

The opportunities for tracking global developments in 3D printing empower the student in the classroom, but eMaking (referring to a practical digital fabrication strategy embedded in the global digital environment) takes student learning outside the studio and into the global digital environment, opening up learning opportunities that contribute to changing student perspective. In design teaching, external feedback has traditionally been provided by real world client projects, however, there are many challenges associated with this strategy [14] as it relies on considerable organisation management from the lecturer and a suitable client, frequently creating conflicts between learning aims and objectives and the values and priorities of the client. eMaking provides alternative opportunities for external interaction. For example, 3D computer assemblies (multiple part models) can be exported as a single part and uploaded onto an international online service provider. The two most significant providers at this time are Shapeways and iMaterialise. Dutch company Shapeways launched its online 3D printing service in 2009, providing industry subsidized printing, introducing nylon products initially, and metals and ceramics since. In four years they have printed over a million objects and been joined by several other online service providers, such as iMaterialise, and it is these services that has enabled a democratised uptake of digital making in undergraduate education. Students at Griffith University open their own account, can upload their model–approved or not by the lecturer–and have it checked by the provider. They then get objective feedback on the viability of their model in terms of printing, and can then choose to print it in a variety of materials. These providers have large build space machines and have additional technologies to FDM, such as selective laser sintering (SLS), which builds the object from powdered material fused into its form in layers by a laser. As this technology supports the printing of assemblies as a single part, students can create complex models with interconnected components, as shown in the model created by a first year Product Design student in Figure 6. In this case, the student had to alter the tolerance in the hinging on the model before it would successfully print.

Figure 6. (**a**) 3D Computer model designed and modeled by first year student, Megan Rowe; (**b**) 3D print of hinged model created by Megan Rowe printed by Shapeways.

Figure 7. Example of a build problem (**a**) and the Shapeways problem report (**b**)



Unless the data provided meets the constraints of the particular technology chosen and the restrictions that apply to that specific material, the object will not be printed, as shown in Figure 7 where the wall thickness in parts of the model were insufficient. The student can refine the data and resubmit, independent of the lecturer. This significantly changes the relationship of the student to the lecturer and to their own learning as the student learns about the constraints or advantages for their design before the lecturer.

Working with international providers, such as Shapeways and iMaterialise, places the student outside the university environment and within a global environment. eMaking takes this a step further by facilitating shared global design practice and in particular learning experiences. For around five years a global design studio has been operating in collaboration between universities, real world clients and working production facilities [15]. In this initiative, partner institutions were chosen from around the world. A shared virtual design studio project was created to operate 24 h a day, coming online in different parts of the globe in the different time zones. One of the challenges of working within this international virtual design studio is maintaining the iterative screen to reality process needed with the design of physical objects. Three-dimensional printing creates that link and allows for design ideas to be shared both on screen and off, particularly where issues of communication across languages are involved. It opens up opportunities for online learning at another level that have implications for other disciplines.

This type of activity provides not only design learning, but also opens the curriculum up to internationalisation. Working with students, manufacturers, and clients from different continents requires a corresponding drive to include a cultural understanding of the background of the partners. Design in context for this form of eLearning needs to broaden to ensure not only a historical context, but, also, a cultural context. For the partnership to be effective, learning has to go beyond studying examples of design from other countries to exploring and understanding the behaviour and expectations of different cultures [16]. Group working takes on a new perspective.

4. eLearning, eMaking Changing the Students' Understanding of the World and the Role of the Designer

4.1. Learning about Sustainability through eLearning and 3D Printing

In the last six years the attitudes towards sustainable design practice have changed. Legislation in Europe has been a driver for change, with manufacturers now responsible for products at the end of life. Design for disassembly and products to be repaired either by the manufacturer, or even the customer, are becoming more prevalent and product service system thinking is replacing the cradle to grave model of design. At the same time, there has been an upsurge in interest in making. Since 2006, the 'Maker Society' has grown to the point where the regular Maker Fairs in the US have upward of 160,000 people attend, and the online 3D printing service provider, Shapeways, has more than 150,000 virtual models uploaded to its site, predominantly by the general public. eMaking in the studio, particularly with 3D printing, connects design students with that movement.

For design education, the sustainability imperative gradually emerged between 2000 and 2010 as a shift in design education projects from commercial to socially responsible. Even the nineties design celebrity Philippe Starck changed his outlook stating: "We have to replace beauty, which is a cultural concept, with goodness, which is a humanist concept" [17]. The student designer is no longer encouraged to emulate iconic designers, but to look towards the complexities of designing within social and environmental responsibilities whilst still meeting the economic viability imperative behind the creation of products.

The book Natural Capitalism: The Next Industrial Revolution [18] highlighted the product service systems approach as a design response to the sustainability imperative, with services over products. From the design educator's point of view, this heralded the need to teach students to apply design thinking to much broader commercial and business issues, and questioned the teaching of traditional production areas within design education.

Three-dimensional printing provides a new starting point for teaching about meeting the sustainability imperative as it can potentially revolutionise production and design by fundamentally changing how businesses operate. Hugh Aldersley-Williams, in the RSA 'The New Tin Ear: Manufacturing, Materials and the Rise of the User-Maker', suggested that the industrial revolution created a 'temporary interlude' that will recede as distributed manufacturing again becomes prevalent and demand for mass customisation replaces mass production because of 3D printing [19]. It is a challenging concept for students and therefore an interesting teaching tool. All products are designed in response to their method of production and distribution. Not only will all products need to be redesigned if 3D printing and digital communication continues to develop as it is, but the entire way design is organized and products distributed will have to be rethought. The spare parts industry is a good example. Currently, multiple replacement parts are made at the same time as the original objects they are designed to service, then stored and shipped out as needed. With global digital communication and digital fabrication, it is possible to now store the data files for those objects and print them singly at the destination they are required on demand. No moulds will need to be retained and no-one will have to judge in advance how many of each item may be required over the years. This affects not only design and manufacturing, but logistics and digital communications as well. Students studying design will need to be inculcated into a new way of thinking about design, production and distribution that questions every aspect of every product and have a heightened appreciation of the interconnectedness of the digital and the real. Bringing 3D printers into the classroom highlights and addresses this need, embedding eMaking as part of an actively eLearning approach connects the student to the changing digital design and production environment.

The lines of screen to reality between the physical object and the web are also blurring through the advent of ‘Co-design’. Co-design is a practice that is emerging directly as a result of the possibilities provided by 3D Printing to individually print customized objects. Designers set up product parameters online that the consumer can directly interact within to influence the form of their product [20]. This practice is changing how design is taught and further merging the screen and reality, online-offline relationships in design and making.

4.2. Connecting with Society

Contrary to what could be expected with the rise of the Internet and the virtual environment, the Maker Society, as defined by Anderson in his book Makers: The new industrial revolution [21], has not been killed off by the digital, but in contrast is experiencing a resurgence, led by increased communication through Web 2.0 and new digital making opportunities. The barriers between online and offline are becoming blurred in a combined digital and physical environment. Three-dimensional printing is part of this unification and can be an empowering learning tool for anyone, changing their relationship with the virtual and the physical, allowing them to take ideas and thinking from screen to reality and back again in an iterative, connected process. A product design teaching related example of this phenomenon has been the rise of the networked Fab Labs [22]. These were an initiative by Neil Gershenfeld, the Director of the Massachusetts Institute of Technology Centre for Bits and Atoms, to provide open access to high technology digital making equipment. Initially set up as an experiment to meet his academic requirement for community engagement, this project has spread throughout the world, with 117 registered sites, predominantly in Europe and America, with some of the most innovative projects coming out of Fab Labs in more remote locations, such as Afghanistan. CNC routering, laser cutting, digital embroidery, electronics, and 3D printing are provided in a Fab Lab as Gershenfeld suggests that the digital basis for the advanced technology making facilities reconnects the two worlds, digital and physical.

The 3D Digital Media design department at Griffith University supported a trial Fab Lab in Brisbane in February 2013 [23] in conjunction with the digital hub section of the State Library, called The Edge, that has led to the launching of Brisbane's first official Fab Lab. Students will be encouraged to work with The Edge as part of professional practice, providing an alternative interpretation of industrial project work, and allowing them to gain an understanding of the role of Fab Labs in social inclusion and as part of a worldwide movement to provide access to advanced technology for the general public and support individual innovation and the Maker Society.

3D printing as a transformative technology opens up an avenue of study addressing the transferable skills needed to foster an understanding of social and civic responsibilities and human rights that is useful for the lecturer in meeting graduate attributes in this area, as well as in design teaching, and Internet connectivity allow to students to research contemporary issues. For example, studying the potential of 3D printing for humanitarian logistics means students can work at the cutting edge of new developments in logistics worldwide alongside experienced professionals as they are happening now. Students are also introduced through developments in 3D printing to ethical debates, for example, on the potential to use desktop printers to create plastic guns. One Masters student at Griffith in 2013 was interested in the use of biomaterials to create a scaffolding for a damaged heart that was 3D printed to allow the patient's own cells to grow around it. The student was interested in the potential to then alter the structure of a functioning heart and worked with a pathologist and cardiologist to develop and 3D print a provocation piece for discussion on the ethics of human engineering research as shown in Figure 8. This project created links across disciplines within the university between clinicians, design, art, and engineering, and has suggested new directions for postgraduate projects that are beyond the scope of current practice of any of those concerned. It is an example of how 3D printing and eLearning have had an impact on design learning at Griffith University far beyond the physical making of objects in the classroom.

Figure 8. Heart provocation models by MA student Kaecee Fitzgerald (**a**) CAD model; (**b**) 3D print from the CAD model; and (**c**) heart in action showing flow.

(a) **(b)** **(c)**

5. Conclusions

Since 2010, when online service providers began operating effectively, Griffith has introduced 3D printing into the product design curriculum, with the first desktop printers brought into the design studio in 2011. The printers initially appeared to have limited use and potentially very little impact on pedagogy. However, their impact at Griffith cannot be compared to adding the facility for a conventional technology, such as rotational moulding, as 3D printing has not remained as an isolated technology. The practical action research project, run during 2013 to explore changing practice in the design studio, through the introduction of an eLearning strategy based on eMaking, was as a specific response to the changing role of the product designer with 3D printing in conjunction with Web 2.0. Whilst there has been considerable educational research into the use of 3D printing as a visualisation tool in education, for example in the study of mathematics as illustrated by the work of Segerman on the visualisation of equations [24], this study has demonstrated how the technologies support new educational approaches for student centred design eLearning both in the physical studio and as part of the broader design community.

According to Dee Fink, in his text on creating significant learning experiences; "When teachers want students to enhance their human interaction capabilities, they have to find ways to help them become more self-aware and other-aware in relation to the subjects being studied" [25]. eMaking has been shown in this study to provide the lecturer with new ways to create appropriately significant learning opportunities for the current generation of students, to aid deep learning that changes their perspectives. For designers, creating proactive, lifelong learners is central because design involves applying process to practice in new situations with each new design brief. Graduates need to be able to scope a project through initial and self-initiated research, frame a design problem, construct a design brief and map a design development process fed by directed research that they themselves identify. Prescribed projects do not support the student in learning this approach. Shifting the balance of power, enabling proactive, lifelong learners–self-directed and self-motivated–is as vital in design education as is possible for any discipline.

As, fundamentally, 3D printing is being heralded as 'Industrial Revolution 2.0' [21] due to its impact, not only on commercial design and production practices, but also on business practices and distribution - and education. Its applications are not limited to one discipline and, thus, the myriad of projects it affects are too numerous, and the speed with which its influence is spreading is too fast, for a lecturer to track. This study has found that students do bring new examples to the attention of their peers and the lecturer on a daily basis. The lecturer role shifts to facilitator in a studio environment where the responsibility for providing information to the group is shared by the students, where advances in the technology are news to the lecturer and student at the same time, and the student can fact check or supplement any statements made by the lecturer online.

Dee Fink [25] challenges that a rethink of approach is required by faculty in response to the current realities of learning: "Making holistic, multidimensional changes in the way educational programs are created and supported, modifying traditional procedures related to faculty work and to the evaluation of teaching, establishing new centres for instructional development, and coordinating student development with faculty development will require time, energy and commitment" and argues for the benefits of creating additional and innovative learning opportunities: "When a teacher finds a way to help students achieve one kind of learning, this can in fact enhance, not decrease, student achievement in the other kinds of learning." eMaking as part of an eLearning strategy will require the lecturer to operate differently than in conventional learning, but if designed with the aim to improve the wellbeing of students and lecturers has the potential to bring a range of learning benefits from changed practice. Rethinking learning with eMaking is not only driven by the development of making skills, or even design skills that stretch into systems thinking, but also transferable skills, such as cultural understanding and the ability to map and engage with proactive learning. Beyond that, it connects students to new developments that are radically rewriting their discipline and introduces it in an accessible way. Far more than for other areas of design, 3D printing and eMaking is providing the opportunity–even necessity–for a shift in practice that ensures the student is at the centre of their learning, in control of their learning, and a proactive partner in creating and supporting the learning environment.

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Conflicts of Interest

The author declares no conflict of interest.

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Images

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