Digital technologies and 4D customized design: challenging conventions with responsive design

Novak, James I and Loy, Jennifer. 2018. Digital technologies and 4D customized design: challenging conventions with responsive design. In Bryan, Valerie C, Musgrove, Ann T and Powers, Jillian R (ed), *Handbook of research on human development in the digital age*, IGI Global, Hershey, Pa., pp.403-426.

DOI: 10.4018/978-1-5225-2838-8.ch018

Handbook of Research on Human Development in the Digital Age

Valerie C. Bryan
Florida Atlantic University, USA

Ann T. Musgrove
Florida Atlantic University, USA

Jillian R. Powers
Florida Atlantic University, USA

A volume in the Advances in Human and Social Aspects of Technology (AHSAT) Book Series

Published in the United States of America by
IGI Global
Information Science Reference (an imprint of IGI Global)
701 E. Chocolate Avenue
Hershey PA, USA 17033
Tel: 717-533-8845
Fax: 717-533-8661
E-mail: cust@igi-global.com
Web site: http://www.igi-global.com

Library of Congress Cataloging-in-Publication Data

Names: Bryan, Valerie C., editor. | Musgrove, Ann T., 1956- editor. | Powers, Jillian R., 1972- editor.
Title: Handbook of research on human development in the digital age / Valerie C. Bryan, Ann T. Musgrove, and Jillian R. Powers, editors.
Description: Hershey : Information Science Reference, [2017]
Identifiers: LCCN 2017010367| ISBN 9781522528388 (hardcover) | ISBN 9781522528395 (ebook)
Subjects: LCSH: Computer-assisted instruction--Psychological aspects. | Educational psychology. | Developmental psychology.
Classification: LCC LB1028.5 .H3164 2017 | DDC 371.33/4019--dc23 LC record available at https://lccn.loc.gov/2017010367

This book is published in the IGI Global book series Advances in Human and Social Aspects of Technology (AHSAT) (ISSN: 2328-1316; eISSN: 2328-1324)

British Cataloguing in Publication Data
A Cataloguing in Publication record for this book is available from the British Library.

All work contributed to this book is new, previously-unpublished material. The views expressed in this book are those of the authors, but not necessarily of the publisher.

For electronic access to this publication, please contact: eresources@igi-global.com.

Chapter 18

Digital Technologies and 4D Customized Design:
Challenging Conventions With Responsive Design

James I. Novak
Griffith University, Australia

Jennifer Loy
University of Technology Sydney, Australia

ABSTRACT

Digital design tools are rapidly changing and blurring the boundaries between design disciplines. By extension, the relationship between humans and products is also changing, to the point where opportunities are emerging for products that can co-evolve with their human users over time. This chapter highlights how these '4D products' respond to the vision laid out three decades ago for ubiquitous computing, and have the potential to enhance human experiences by creating more seamless human-centered relationships with technology. These developments are examined in context with broader shifts in sociocultural and environmental concerns, as well as similar developments being researched in Responsive Architecture, 4D printing and systems designed to empower individuals during the design process through interactive, parametric model platforms. Technology is fundamentally changing the way designers create physical products, and new understandings are needed to positively guide these changes.

INTRODUCTION

Human-centered product design, where the end users of a product remain at the forefront of all design decisions, is evolving rapidly as the opportunities of the digital age become better understood. The boundaries between design disciplines are blurring as digital technologies break down traditional practices, creating products that challenge design conventions. This chapter discusses the significance of changes to product design and design systems enabled by digital technologies in relation to human

DOI: 10.4018/978-1-5225-2838-8.ch018

development. In particular it considers how the relationship between people and products could change with a shift in thinking from static, resolved outcomes to digitally enabled products, in particular ones that are capable of changing over time—4D products—and the implications of that change. This affects the designer-product relationship, and the customer-product relationship as well as the systems within which they operate.

Examples of practice-led design research in the latter part of this chapter introduce different approaches to the development of 4D products. These provide starting points for a practical and theoretical framework for design research and education in the changing digital design environment from user experience, through interaction, to a digitally enabled product service system. Designs based on ubiquitous computing allow for the development of products that change the relationships and experiences in human-centered product design. Based on additive manufacturing processes, 4D printing allows for products that morph under certain conditions, as do examples from the field of responsive architecture (Meagher, 2014). These approaches challenge designers to think less about static, final outcomes, and more about the opportunities for objects to evolve into different states through their lifespan. As such, designers are called on to develop systems and parameters for product permutations, rather than fixed product outcomes, and rethink their role and relationship to products and users, and the impact of their designs in a digitally connected world. This aligns with current theory on the relationship between human evolution and digital technologies.

HUMAN EVOLUTION IN A DIGITAL ERA

There is an argument that the biological mechanisms that have governed human evolution for 3.5 million years have been disrupted by the development of human cognition and cultural behaviors, overwhelming natural systems, and resulting in what is termed "Human Evolutionary Stasis" (Powell, 2012). The suggestion is that humans have the ability to collectively circumvent the challenges they may otherwise face as individuals, and that this is impacting the biological evolution of the species as a whole.

The human organism is a paradigmatic case of ontogenetic adaptation: thanks to an enormously flexible cognitive and behavioral repertoire, including the ability to acquire and transmit cumulative (intergenerational) cultural adaptations, humans can survive and reproduce across a wide range of otherwise hostile developmental conditions. (Powell, 2012, p. 150)

Yet the impact of technological development on early learning and ontogenetic adaptation could be argued to be challenging the idea of a stalled evolution of the species. If human evolution is seen as referring to its adaptation to the complex systems in which humans operate, then human development in a technological age is evidenced by the ability of each successive generation to adapt more quickly to evolving digital systems:

Gen Y have grown up in a world of rapid technological advances affecting the way they learn, their approach to knowledge acquisition and the forms of interaction between themselves… as a result of their techno-dependency and the fact they are accustomed to using computers and Internet to perform any given task, Gen Y has formed unique characteristics and competences… (Petrova, 2014, p. 525)

As the pace of technological innovation increases, there is a tendency to assume that humans will continue to adapt cognitively to keep pace, yet, as suggested by Al Gore, humans will soon be in a situation where their cognitive abilities are surpassed by their own inventions:

The emergence of a planet-wide electronic communications grid connecting the thoughts and feelings of billions of people and linking them to rapidly expanding volumes of data, to a fast growing world of sensors being embedded ubiquitously throughout the world, and to increasingly intelligent devices, robots, and thinking machines, the smartest of which already exceed the capabilities of humans….and may soon surpass us in manifestations of intelligence we have always assumed would remain the unique province of our species. (Gore, 2013, xiv)

For designers operating in a world where technological innovation could assume an intelligence that drives change itself—beyond human cognition—it is tempting to focus on the potential of technology to create new object mitigated interactions and complex support systems without taking into account the implications for humanity. This is a pitfall into which the commercial world has already fallen: “Could the people who began the Industrial Revolution foresee the ecological effects and loss of life caused by the rise of factory systems, chemical manufacturing, machine tools, coal burning, and mining?” (St Clair, 2016, p. 42) The publication of *Wealth of Nations* through to the development of the moving assembly line by Ford (Sparke, 1987) and the establishment of the Ford Motor Co in 1903 could hardly have been expected to lead to the economic problems for Detroit in the 1950s. Understanding economic and social implications in a period of significant change are consistently problematic. Understanding the implications for the development of the human psyche, already linked to cognitive behavior changes, brought on by technological immersion at an early age of subsequent generations in a rapidly evolving digital age, are nigh on impossible. Who could have predicted the overwhelming initial response to the launch of the augmented reality Nintendo game of Pokémon Go (*Pokemon Go*, 2016) in 2016 and the unexpected consequences of players, such as being injured through inattention to their surroundings and collaborating with strangers, all in the pursuit of Pokémon?

The challenge for all people, from designers creating new products to the end users openly embracing them, is that “we are morphing so fast that our ability to invent new things outpaces the rate we can civilize them. These days it takes us a decade after a technology appears to develop a social consensus on what it means” (Kelly, 2010, p.3). Similarly Gore argues that there have never before been “so many revolutionary changes unfolding simultaneously and converging with one another” and that there is a “clear consensus that the future now emerging will be extremely different from anything we have ever known in the past. It is a difference not of degree but of kind” (2013, xv). His reasoning is that global digital connectivity, the expansion of information collection and data mining techniques are fostering the emergence of a collective “global mind” that requires a re-imagining of human interaction and organization (Gore, 2013).

One of the inevitabilities widely assumed over the last 30 years has been cultural homogenization through globalization. A consequence of the digital connectivity described by Gore is that country borders become porous, and after an unprecedented era of relative stability across the globe allowing for increased trade and co-operation, the predictions have been for a linear pattern of growth in the amalgamation of individual countries into larger trade groups, such as in the European Union. Yet the signs in 2016 are that globalization is facing a crisis. The fallout from the Brexit vote, the crisis in France under the onslaught of ISIS, and the concerns in Germany over their open borders policy during the Syrian refugee crisis provide contrary indications that suggest the possibility of a trend reversal.

Within product design, there is evidence of a corresponding drive for diversity over homogenization, with cultural difference and individuality paradoxically supported by the very digital technology predicted to alienate people from production. While Aldersey-Williams' (2011) predictions of a return to a pre-industrial era of individual craftsmanship may have sounded farfetched in 2011, the exponential growth of the digitally enabled maker society highlighted by Anderson (2012) suggests there could be a change in paradigm, where people become significantly more engaged in the design and development of the products around them.

This shift in thinking is already resulting in a new breed of digitally enabled product designer, who uses generative modeling techniques as part of their process, only possible because new Computer-Aided Design (CAD) software and 3D printing (additive manufacturing) allows for individual objects to be built without tooling. Designers such as Lionel Dean (Dean, 2016) and Fung Kwok Pan ("Fung Kwok Pan: Fluid Vase," 2010) evidence this trend where the designer and consumer both contribute to decision making on the form of the product, communicating through digital platforms. Also in both these cases, the designers are exploring the interaction itself and the power of digital communication facilitated by additive manufacturing. Recognizing the human-centered aspects to the development of products in a digital age remains at the core of the role of the designer. Yet the nature of that human-centered focus is changing as the digital age matures, and designers will have to renegotiate their role and responsibilities alongside it, while also keeping pace with broader design theory including the sustainability imperative and systems thinking.

PEOPLE, PRODUCTS AND SYSTEMS

Over the last 20 years, design theory has moved the focus of design from discrete products to the design of systems (Hawken, Lovins & Lovins, 2000). This strategy began as a response to economic drivers with practices such as "Lean Manufacturing" and "Just in Time" extending out to the re-evaluation of the supply chain to a value chain approach, but it gained momentum with the sustainability imperative introduced to design and manufacturing in response to the Brundtland commission report in 1987. Technology and the digital age in which humans now live is allowing for a more holistic understanding of the lifecycle of designs not previously possible, with quantifiable measurement and standardization at all stages making designers increasingly accountable for their decisions. It is only in the current era that this complex connectivity is becoming overt, changing the relationship between designers, products and consumers. However, these rapid changes in information gathering and technical possibility need to take into account the corresponding changes to the collective human psyche mentioned in the previous section, as well as the specific experiences of individuals. The scope, pace and scale of change currently being experienced have not previously been part of human evolutionary history. Therefore the impact of current thinking in technology as it informs the design of products and its subsequent impact on humans requires sufficient attention, and the responsibilities designers face for affecting ontogenetic adaptation need to be addressed.

It is essential for humans at this time in our evolution to begin to identify what is being lost through our utter dependence on technology and to determine how it may affect humanity long term. Furthermore, *we must not think only of the long-term effects: we must also ask ourselves about the intentions of our actions. (St Clair, 2016, p. 43)*

The impact on human development and the realities of the human response to the covert introduction of technology into everyday living is not linear and predictable. There are unexpected consequences, just as there were with the impact of manufacturing on the health of the planet, and the human response can be equally unexpected, even perverse, and often emotional—as illustrated by the recent resurgence in “low-tech” vinyl record sales, for example, despite the proliferation of high quality digital music. One of the issues is the technology promise tends to focus on ideas of simplifying the human experience, and reducing choice, rather than focusing on user experience and the individual needs of people to be unique and valued for their differences. The growing move to cloud-based services and intangible goods can clash with a human need to be connected to the tangible world. Focusing on the direct marketing aspects in transactions with online travel companies, clothing shops and bookshops, ignores the very human need for the hunt—for meeting the curiosity cognitive driver identified in the updated Maslow’s hierarchy (McLeod, 2016).

The problem of information technology (IT) driven change is that the user-centered experiences are rarely understood or catered for, let alone central to the product discourse. Digitally enabled user-experience products have typically evolved from user-interface, screen-based product design. IT professionals are not traditionally trained to focus on the user experience beyond the boundaries of the screen in the way that product designers are, but, equally, product design disciplines do not usually contain the technical understanding of electronics and coding needed to maximize the possibilities for digitally enabled design. Yet, that human understanding and focus are vital for design—both in a business sense and in a broader, social and human development point of view.

As technology evolves, designers and IT specialists alike have the opportunity to integrate more functionality, data capture, information sorting and communication into everyday products, but the challenge is how to keep a level head to maximize integrated digital technologies for actual benefit to the users. Evgeny Morozov describes this modern dilemma as “solutionism”: when a designer “presumes rather than investigates the problems that [the product] is trying to solve” (2013, p. 6) and too readily adopts new technologies without thoroughly understanding the human-centered problem—if there is even a problem at all. With the rapid pace of technological adoption, the opportunity to slow down to understand all facets of a problem as suggested by Morozov can be a challenge. If one of the fundamental characteristics predicted for the post digital revolution era is that technology will evolve at an ever more rapid pace, then creating products that center the human experience within that change become even more important. Helping individuals to define and support their identities should be a driver for design in an era of homogenization. Equally, supporting the confidence of the individual to navigate in a technological era should be vital for designers, rather than losing all decision making power to machines, as emphasized by St Clair (2016).

Developing users who are effective lifelong learners matters in a time of technological development, as does designing products that are fully expected to evolve as situations and needs change. Developing lifelong learners depends on empowering the individual to take control of their own learning going forward. In her work on student learning in higher education, Weimer (2002) discusses the importance of shifting the balance of power in the learning experience from the lecturer to the student. She argues that this enables the student to build resilience in learning terms to facing new challenges that are initially difficult. If this approach is applied to design, then for designers to create products that allow for an evolution of use or interaction, they must fundamentally empower the user during use, rather than disempowering the individual in service of the organizational system. This making of the individual experience subservient to support the efficiencies in management practices is short sighted and could well lead to a very human rejection of technologically based products.

Collaboration between disciplines in developing technology-driven products is becoming essential in the current sociocultural and environmental sustainability context (Loy, Canning, & Haskell, 2016). The goal is arguably to reinforce identity and sense of self, supporting diversity in a global community, by using technology to collaborate to enhance the human experience and sense of engagement and responsibility, rather than to make interaction more efficient, or organizationally more effective.

DESIGNING IN CONTEXT

For the last 20 years, designers have been striving to design more "lightly"; that is, to design to reduce the impact of the manufacture, use, and disposal of their products on the environment. This has extended to include the social impact of their products for their full lifecycle right from the impact on communities of sourcing raw materials (e.g. foreign-owned mono-culture plantations on local communities dependent on natural, diverse forestation, or the mining of bauxite for aluminum smelting on aboriginal communities and farming communities). In *Design Activism: Beautiful Strangeness in a Sustainable World*, Fuad-Luke (2009) looked at the discourses and context informing design strategies at a point in time. Hindsight highlights the unexpected consequences of design decisions, suggesting that the information available at a point in time is context specific, and that there could be layers of impact initially unknown that could eventually become clear. The impact on human development is one of those layers. So, just as sustainable design theory has shifted the focus of product design from a "cradle to grave" approach to a "cradle to cradle" approach (Braungart & McDonough, 2002), then correspondingly an approach to design taking into account human development needs to be considered equally "lightly". "In considering 'value' during product definition, then, we should expand this usual definition to include intangibles such as personal aspirations and model codes of behavior" (Rowland, Goodman, Charlier, Light, & Lui, 2015, p. 187).

This moral imperative suggests designers need to consider their work even more holistically, as part of a complex team that includes sociologists and psychologists. However, with the bourgeoning digital technology environment, IT specialists need to be integrated into that team more effectively than in current practice. Where user-interface design is morphing into user-experience design, the body of knowledge in product design is lost or diluted. A new approach is needed, perhaps one whereby designers are able to adopt new technologies to take greater control of—or at least have a greater understanding of—the design solution in its entirety. Without a vantage point to see both the problem and solution in entirety, it is difficult for a designer to appreciate the impact of their designs on the users, and on stakeholders indirectly affected during the product's lifecycle.

Designer-maker John Makepeace (1995) described good design as being informed by the knowledge and understandings available at a particular point in time. He also argued that good design embodies the aspirations for society of the period, expressing its values and ideals. Rowland et al. suggest that ideas of value and aspirations are linked to what people care about: "If your business model involves helping people feel closer to specific dreams, it's worth taking time to clearly articulate what those dreams are" (Rowland et al., 2015, p.187). Whether individuals currently care sufficiently about the impact of the digital age on human development in order for it to be overtly mandated as a design imperative is open to debate, but for the design discipline, leading the development of products post the digital revolution, these issues need to be articulated and discussed. Designers working to Makepeace's ideal should not ignore the potential of their work to influence human development and, equally, should recognize that where humans are concerned, the impacts are impossible to predict and they should tread lightly.

The main learning from the pace of technological development is that change is perpetual, and the current rate of change should be a key consideration for the development of products. Aligned with the recognition that agile and evolving products are part of a product service systems approach is the planned "graceful degradation" of products (products that decline to obsolescence with as little harm as possible) and the "cradle to cradle" product lifecycle ideal that addresses the sustainability imperative (economic, environmental and sociological). Extending the essential criteria of this approach to a new era of data generation, collection and analysis, and technologically enhanced functionality, designers need to focus on the fundamentals of really designing for people and for change, not impose values and behaviors on users for the sake of efficiencies and technical enhancements. Just as sustainability theory has been extended to include socio-cultural sustainability in the face of challenges to cultural diversity brought about by digital connectivity and globalization (Loy et al., 2016), so design theory needs to respond to current thinking around supporting the development of the human psyche, and human learning after the digital revolution. The following sections of this chapter describe ideas on the development of responsive products as the role and responsibilities of the designer change again.

THE CHANGING ROLE OF DESIGNERS

A key theme of this chapter is that technological development is becoming symbiotic with humanity. Indeed, Kelly, cofounder of *Wired* magazine, argues that technology can be viewed as a living force:

The technium [the broader interconnected system of technologies] is now as great a force in our world as nature, and our response to the technium should be similar to our response to nature. We can't demand that technology obey us any more than we can demand that life obey us. Sometimes we should surrender to its lead and bask in its abundance, and sometimes we should try to bend its natural course to meet our own. (Kelly, 2010, p. 17)

In Kelly's view, if technology is considered as a living force then the next logical step forward is for "living products" or products that act independently, directed by technologies referred to as ubiquitous computing. The term ubiquitous computing can be used interchangeably with the terms pervasive computing and physical computing (Greenfield, 2006, p. 1), and is credited to the seminal paper by Mark Weiser in 1991 titled "The Computer for the 21st Century." In this paper Weiser describes the most profound technologies as "…those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it" (1991, p.1). These go beyond conspicuous computers, such as smart phones and tablets, to more rudimentary products that have sensors and computing power in them, as seamlessly gathering and processing data, and reacting to this information.

The Internet of Things (IoT) is an extension of ubiquitous computing, with the key difference described by Adrian McEwen and Hakim Cassimally as the element of "the Internet" (2013, p. 10). Assa Ashuach's AI light (*Assa Ashuach Studio*, 2016) is an example of ubiquitous computing because it responds to movement in a room autonomously, without needing to be connected to the Internet for control. In contrast, home LED lighting solutions that can be controlled via mobile phone applications, such as the Philips Hue (*Philips Hue*, 2016) are examples of Internet of Things solutions where the product relies on being able to connect to other devices via the Internet in order to function.

While it is clear that many elements of theorist Weiser's ubiquitous computing vision from the early 1990s have come to pass, in particular the concepts of "tabs [mobile phones], pads [tablet computing] and boards [interactive displays]" (Weiser, 1991, p. 9), the examples of research-led design described in the following section take this vision further. The concepts explore the creation of products embedded with computing technology to add value to users' experiences while remaining relatively inconspicuous during daily life. As with many digital technologies, ubiquitous computing has been a research focus for IT and computer science disciplines, with innovation largely a response to the opportunities provided by new technologies and reduced size of processors and sensors in line with Moore's Law. User-driven design has taken a back seat. However, Adam Greenfield (2006, p. 3) and Peter Nowak (2015, p. 7) argue that the majority of technical hurdles to ubiquitous computing in products have now been overcome, suggesting it is time for designers to determine how ubiquitous computing can enhance the experiences of consumers. As Greenfield asserts, "All the necessary pieces of the puzzle are sitting there on the tabletop, waiting for us to pick them up and put them together" (2006, p. 92).

One of the challenges for designers in creating ubiquitous computing products is the quantity and variation of skills involved in working in this field. In addition to the traditional understanding of form, function, materials and sustainability familiar to industrial designers, there is an added necessity to work with electrical hardware, computer programs, interfaces and Internet protocols. Splitting the product into separate components and responsibilities, as is historically the case in product development where industrial designers, engineers, IT, graphic designers, manufacturers and numerous other parties work on aspects of the same product in relative isolation, is unlikely to result in the high value output described by visions of ubiquitous computing. The results can be feature creep or solutionism, rather than the genuine engagement with improving user experience needed for a paradigm shift. This is because, by definition, a product designed to seamlessly integrate into the complex daily lives of humans is made up of numerous elements, systems and sub-systems that must operate as a unified whole, or else expose themselves through glitches and errors that break the illusion of being at one with the surrounding environment. The fractured growth of the field has yet to provide a unified, informed approach sufficient to meet the challenges involved.

Bruce Sterling describes current offerings of ubiquitous computing products as low-level gizmos—products that "have enough functionality to actively nag people. Their deployment demands extensive, sustained interaction: upgrades, grooming, plug-ins, plug-outs, unsought messages, security threats and so forth" (Sterling, 2005, p. 11). An example would be the mobile phone, a so-called "smart" device that demands attention with ring tones, flashing lights, vibrations and messages. While alerts may relate to a human-centered social contact, the phone itself may send alerts to demand an update to an app, its system, or security settings. Most smart objects and humans are still essentially discrete entities, and while Kevin Kelly describes humans as "coevolving with our technology" (2010, p. 37), the technology is not yet a reflection of humanity. Sterling describes this when he says:

It's mentally easier to divide humans and objects than to understand them as a comprehensive and interdependent system: people are alive, objects are inert, people can think, objects just lie there. But this *taxonomical division blinds us to the ways and means by which objects do change, and it obscures the areas of intervention where design can reshape things. (Sterling, 2005, pp. 8-9)*

Perhaps the struggle for designers in developing innovative ubiquitous computing products lies in historical baggage, including the term "industrial" design. In Stuart Walker's book *Sustainable by Design: Explorations in Theory and Practice*, this concept is explored from a sustainability perspective, but applies equally to the struggles in adopting new digital technologies. Walker argues:

The very term 'industrial design' brings with it a great deal of baggage. It defines an approach, carrying with it a set of expectations, and it represents a particular set of knowledge and skills. Industrial design is closely linked, as a term and as a discipline, with the development of mass production and consumer goods in the early years of the 20th century. It is generally understood as the design of products for large-scale distribution and it is commonly described as a service profession to the manufacturing industry. (2006, p. 35)

However, design is no longer just industrial in nature, nor is it necessarily focused on mass production or even the creation of physical objects. The digital revolution provides a paradigm shift away from focusing on the atoms of products to the bits of technology. Gore cites an example of this shift in his book *The Future*, through the company Narrative Science, which uses computer algorithms to write entirely new newspaper and magazine articles on topics ranging from sports to finance. Gore observes, "The few human writers who work for the company have become 'meta-journalists' who design the templates, frames, and angles into which the algorithm inserts data" (2013, p. 8). The meta-journalists, or rather, their algorithms, can now write millions of stories at a time rather than just one, with huge implications for the future employment opportunities for journalists. Should this trend to rethink entire operational approaches to conventional disciplines spread as is predicted by Gore, all industries, including industrial design, must adapt or risk becoming obsolete to computers.

Adapting is made all the more challenging because of the rapid progress of technologies. No sooner has the latest software upgrade to a smart phone been delivered than a new model is created with yet more features and power. This is also the case with software. The digital tools used by industrial designers, including optimized software to keep pace with technological developments such as 3D printing (additive manufacturing), 3D scanning, virtual reality, and the Internet of Things challenge designers in staying current and relevant in their practice. An example to illustrate how industrial design is changing as a profession is found in the evolution of bicycle design. Bicycles are industrial products, with their materials, construction, and form a result of the machine age. While new materials have been applied to bicycle frames over the decades, and there are multiple configurations of tube cross-sections and frame size, bicycle design has remained relatively unchanged over the last hundred years. Under the mass production paradigm, bicycle manufacturers need to sell a large number of the same bicycle to offset the expense of tooling its individual components. To reduce costs, models are produced in a limited range of sizes. Customers choose the closest-fitting size for their anthropometry, but frames are rarely perfect for the rider because of different body shapes, so adjustments are made through components such as the saddle and handlebars, to create as close to fit as possible. This longstanding model of practice is poised for significant change—in part because of the opportunities provided by additive manufacturing (3D printing) technology, and in part because of the advances in 3D CAD tools. For example, topological optimization software utilizes mathematics and computer simulation to calculate "the 'logical place' for material—normally using iterative steps and finite element analysis" (Renishaw, 2014). The design of a product—from both a functional and an aesthetic point of view—can theoretically be calculated by computer, and because of the opportunities to use additive manufacturing to bring complexity into the real world, a topologically optimized seat post by Renishaw can be designed 44% lighter than before (Renishaw, 2014). From the digital design perspective, if software using topology optimization is creating complex lightweight forms for the bicycle frame previously impossible to manufacture, then consider the following:

1. If the computer can automatically design a better product from an engineering perspective than a human being, does this reduce the need for designers?
2. If additive manufacturing allows for every design to be different, will designers be left to micromanage every variation of a design rather than creating a single static product and moving on to something else?

This shift could be viewed as confrontational for the design discipline. However, depending on the response of the industrial design discipline, it is possible that the designer's role could evolve positively alongside emerging digital tools. To research this, the customization of products through data manipulation has been investigated, looking at projects such as "Fab Form" (Shugrina, Shamir, & Matusik, 2015), "Project Shapeshifter" (AutoDesk, 2016), and "Parametric Parts" (*Parametric Parts*, 2016). These projects use parametric relationships as constraints while limiting objects to a range of values known to produce manufacturable results. This means a novice user can, within limits, customize the CAD data for a pre-defined product within a simplified user interface. A shift in the industrial designer's role is required because these systems mean the designer is no longer creating a single 3D model of a final product, but is responsible for creating the system whereby a product concept can be manipulated into forms not necessarily envisaged by the designer. This is referred to as "Meta-Design" (Bezirtzis, Lewis, & Christeson, 2007; Fischer & Scharff, 2000). A second shift is that the customer is a participant in the design process, as discussed by Tseng, Jiao and Wang (2010, p. 177) and Jack Hu (2013, p. 6)—no longer being limited in what they must purchase by designers, but actively involved in creating it themselves. This shift from consumer to "prosumer" (Abel, Evers, Klaassen, & Troxler, 2011; Ahluwalia & Miller, 2014) radically transforms the relationship between people buying products and those creating products to sell. It is also part of a response to the imperative to create proactive users, who are invested in the products they use, with potential positive ramifications for the sustainability imperative.

However, the changes confronting modern designers go deeper: "Over the last two decades designers have mastered algorithms alongside visual thinking, and today we can witness the first generation of computational designers mature. The coming generation of designers sees code as a kind of material just as a potter sees clay" (Klanten, Ehmann, & Hanschke, 2011, p. 5). Algorithms and coding have developed in order to create software or control complex electronics. Intuitive visual programming, while not new, is only now becoming readily accessible, with programs such as Scratch (MIT Media Lab, 2016) and App Inventor (MIT, 2015) providing a visual method of coding where blocks of code can be graphically linked together in-tune with designers' visual understanding of the world. Furthermore, Rhino, popular CAD program amongst industrial designers and architects, has a range of plug-in packages including Grasshopper and Firefly, allowing the form of a product to be developed alongside its electronics or mobile application, within the same piece of software. These capabilities are also being newly embedded within PTC's Creo 3D design software through their addition of the "Designworx" Internet of Things platform. In both cases, Arduino and other electronic devices can be directly prototyped and controlled in the real world utilizing plug-ins, allowing the designer to manage additional aspects of the design relating to digital technologies, and rapidly iterate this integrated approach during design development more efficiently than previously. These examples signal a breaking down of barriers between formerly distinct roles, such as Electrical Engineer, Software Developer, User Interface Designer and Industrial Designer, with a single creator able to design, prototype, test and even manufacture complex ubiquitous computing based products. A new breed of industrial designer, the "Digital Technologist" (Loy, Canning, & Little, 2015), is emerging as education responds to these changes.

While designers might have access to a rapidly transforming range of new tools and technologies, it is crucial that human-centered design remains the focus of all design endeavors. How would humans react if simple tasks such as running a bath or making a phone call became part of autonomous systems, and what would be the level of frustration when those autonomous systems break down or misinterpret the sensor data designed to predict a person's needs? No doubt most people with a smart phone have experimented with the voice-recognition features, whether it is Siri on the Apple system, Google Now on Android, or Kortana from Microsoft, and experienced the frustrations of having to repeat the query or speak in an unnatural way in order for the system to "hear" what was being said. These systems highlight how challenging a ubiquitous system could be if it struggled to interpret user needs. Adam Greenfield calls this a needless application of technology complexification, and warns "whatever marginal 'improvement' is enacted by overlaying daily life with digital mediation has to be balanced against the risk of screwing up something that already works, however gracelessly or inelegantly" (2006, p. 125). The design of ubiquitous systems is a delicate balancing act that designers are still working to understand and implement with the kind of finesse imagined by Mark Weiser.

Emerging digital design tools, such as those in Rhino or Creo, will give designers the ability to take a holistic control of product development combined with sensors and data collection tools. However, designers will face a seemingly contradictory challenge—to design "invisible" products that enhance user experiences from the background, while being obvious in function so that they can be understood. As products move towards being truly ubiquitous, consumers will be faced with the challenge of not necessarily knowing if a product they encounter is "smart" or not, or to what degree it might be capable of responding to their needs. Greenfield explains "we should get used to the idea that there will henceforth be little correlation between the appearance of an artifact and its capabilities—no obvious indications as to how to invoke basic functionality nor that the artifact is capable of doing anything at all" (2006, p. 134). Traditionally designers include indicators of how a product functions with a visual language intended to transcend written language and culture. An example would be a handle that indicates where a product should be held, a few raised edges on a plastic enclosure to show how it can be opened, a variation in color or material to suggest where a lid can be removed. These cues replace an instruction manual, as the intention is that the user can unconsciously recognize them through their life experiences. However, how does a designer integrate visual cues describing to someone that in order to have a custom multi-vitamin 3D printed each day, as is under development by researchers at the Nestle Institute of Health Sciences (Boyle, 2014)? They may need to use a variety of inter-connected devices, such as a toilet that can analyze urine, a physical activity tracker, a fridge monitoring the foods consumed, and a pill that will only print in response to a retinal eye scan. Such complex, networked systems are as yet more science fiction than reality, but the individual technologies are possible, and demonstrate the sort of complex interactions that designers will need to consider if ubiquitous computing is embraced by mainstream consumers.

INTRODUCING 4D PRODUCT DESIGN

The authors propose an emerging type of product to fulfill the vision of Mark Weiser's ubiquitous computing—the 4D product. A 4D product may be described as one having "four dimensions, typically the three dimensions of space (length, breadth, and depth) plus time" ("four-dimensional," 2010), with time being the critical factor in this category. Time is not related to the longevity of the product, nor the time to produce it, but the ability for the product to physically evolve over time to suit changes in user needs. The emergence of 4D products is strengthened by the growing interest in 4D printing by digital revolution authors such as Eujin Pei (2014) and Dan Headrick (2015). It also relates to the field of responsive architecture at the "intersection of architecture and computer science... and implies the capacity of the building to respond dynamically to changing stimuli" (Meagher, 2014, p. 95). With relevant literature emerging relatively recently, the relationship between time and products specifically is yet to find a clear voice. With their capacity to seamlessly integrate into existing human experiences, 4D products not only meet the goals of ubiquitous computing, but they are only made possible by the concurrent developments in digital tools for designers.

The origins of 4D products are found in nature: there are numerous living examples of creatures capable of transforming or adapting to their environment in real time, such as color-changing chameleons and the blue-ringed octopus. There is also the example of the Mutable Rain Frog, only discovered in 2006, capable of transforming its skin texture from soft and smooth to sharp and spiny. Even humans are capable of a similar, if smaller, change, as cold, stress, or even euphoria can cause small bumps, known as goosebumps (or goose pimples), to be raised on the skin. This is thought to be left-over reflex from when sapiens were covered in thick hair, and when confronted by a potential predator, their goosebumps would cause the hair to stand out, making the person look more intimidating. This reaction can still be seen in animals such as porcupines and cats. If technology is a natural evolutionary force, and humans have spent millennia surrounded by living organisms capable of rapid and ongoing change, then 4D products could be considered a form of biomimicry inevitable because of technological evolution. To illustrate what a 4D product does and why it represents a shift in product design thinking, the following section provides product examples considered in the context of developments such as responsive architecture, 4D printing, and robotics.

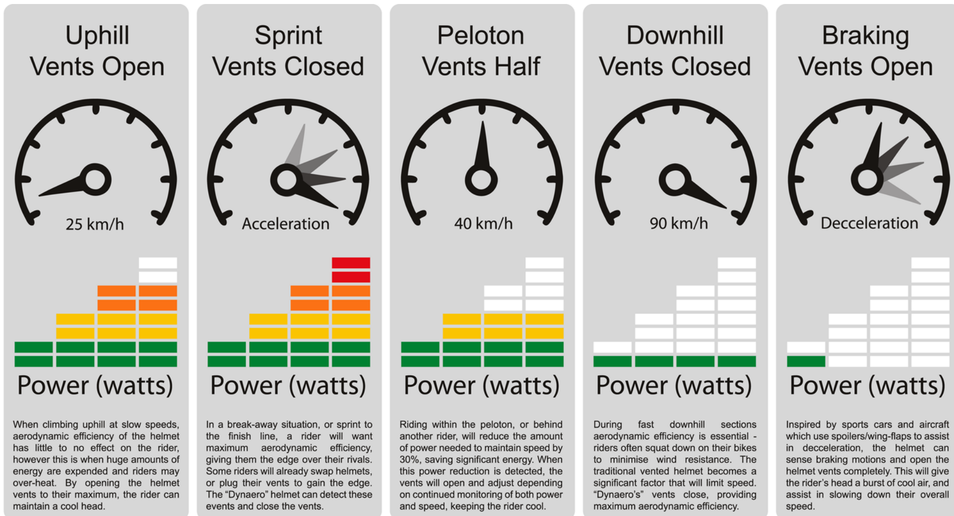
4D DESIGN EXAMPLES

The MIT Media Lab has developed "bioLogic" (Yao et al., 2015), a form of nano-actuator powered by bacteria cells. When exposed to moisture, the cells expand to move thin biofilm materials, working like a hinge to open small vents in clothing. The product operates autonomously without the user needing to control the vents. The effect is similar to the reflexive goosebumps mentioned earlier. Although in the early stages of development, critically this work embodies the concept of being 4D in terms of its human-object relationship changing form continuously over time without specific instructions from the user or even an interface to interact with. Another company experimenting with moving forms is BMW, with both their GINA and more recent Vision Next 100 concept cars. While both cars employ a range of technologies in response to the future of driving and automation, most relevant is their capacity to change their exterior shape for functional purposes. In the case of GINA, the frame is hydraulically controlled to reveal things such as headlights or the engine, or change the shape of the rear of the car to increase traction at high speeds. As with MIT's bioLogic, these form changes are automatically controlled by the car's onboard sensors to improve the driving experience and safety on the road. The Vision Next 100 car adopts the same capabilities of "physically altering the car itself on the go and anticipating and even improving the driver's performance" (Szondy, 2016), with the addition of moving fender skirts to expand the car body as the wheels turn, reducing the drag coefficient to reportedly 0.18 C_d. This feature also improves visibility on the road, revealing a glowing red sub-structure to alert oncoming drivers the car is turning. While such a dynamic car body is yet to be seen on the mainstream market, elements of this transformation can be seen in Formula 1 racing cars. These vehicles have movable rear wing flaps to modify drag for overtaking in certain sections of a race (known as the Drag Reduction System or DRS). Consumer-level cars, such as the Audi TT, are also capable of automatically increasing the rear spoiler angle at high speeds to increase traction and safety. This suggests these life-like movements are slowly finding their way into the mainstream.

Inspired by these conceptual visions of the future, "Dynaero" by James Novak is a research project focusing on the development of a bicycle helmet capable of autonomously adjusting its aerodynamic and thermal regulation properties. The intention is to enhance the performance of the wearer through the use of integrated electronics, sensors and actuators. Research shows that "an aerodynamically efficient helmet can reduce the riders drag by up to 8% of the total aerodynamic drag that a cyclist usually generates" (Alam et al., 2010). During time trial events, cyclists typically wear aerodynamic race helmets with no ventilation, sacrificing thermal regulation for speed over short distances; however over long distances this becomes dangerous for the rider's health so they must sacrifice aerodynamics for helmets with large vents to maintain their body temperature. New helmets from Bell (Star Pro) and KASK (Infinity) have recently emerged allowing riders to manually adjust ventilation with sliders while riding. However, Dynaero draws on recent computing developments in cycling, where sensors relay data on the bodily responses of the cyclist and their bicycle during performance to the support team. Dynaero uses this data to create a responsive helmet that automatically adjusts its vents based on the riders' data, and independent of that rider or even the support team within a predetermined system. This ensures accuracy in using the data patterns to adjust the vents, rather than relying on rider awareness in the heat of competition (Figure 1).

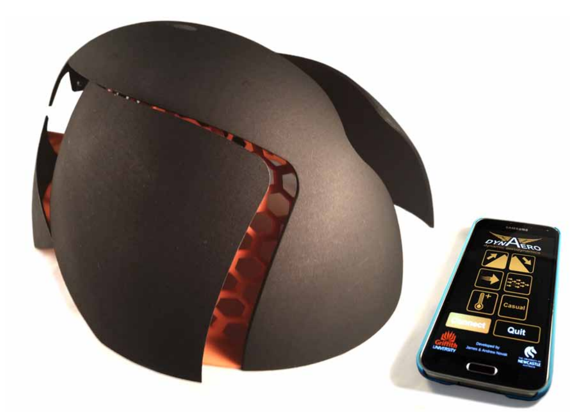
The current working prototype of Dynaero (Figure 2) operates from a custom-designed mobile application and uses the built-in mobile phone sensors to calculate the rider's movements, sending a signal to the helmet via Bluetooth technology to control the opening angle of the large vents. The full design of this system, including both hardware and software, has been created by Novak through the use of graphical tools such as MIT App Inventor and Rhino with Grasshopper discussed previously, exemplifying the way in which designers are becoming empowered to control a greater breadth of the design process through new digital tools. While the prototype is linked to a mobile phone, the final product would be driven by its own sensors and expanded to engage with a variety of common sensors already used by cyclists and transmitting and recording using wireless signals, such as Bluetooth. As such, this project is an example of a product that upholds the ubiquitous computing vision—the helmet responds autonomously to changes in the riders' needs, with its own sensors, and those already installed on a bicycle, communicating simultaneously with the helmet to determine the second-by-second optimum position of the openings. In this way, just like the previous examples from MIT and BMW, the athlete can be immersed in the experience of riding without distraction, yet their performance and safety is improved. Such an "awareable" (i.e., a wearable technology that is itself aware of its surroundings or use) device aims to reduce the attentive demands of the user by raising the "awareness" of the products.

Figure 1. James Novak, Key stages of elite cycling races with relevant speed and power information indicating specific combinations that can be used to control air vents



There are key criteria for the design of 4D products (as defined in this chapter). Fundamentally, a 4D product must be human-centered in this digitally enabled era. It must physically adapt over time—this emerging field is not concerned with software responses alone, such as notifications or other methods of alerting a user as currently utilized by gizmos such as smart phones. The product must autonomously analyze its situation based on the information from sensors, and reflexively respond through actuators. As such, 4D products are inherently tangible and tactile, and act symbiotically with the human user. Adam Greenfield suggests that the word "user" is inadequate to describe these new relationships with the ubiquitous computing objects; "the whole point of designing ubiquitous systems was that they would be ambient, peripheral, and not focally attended to in the way that something actively "used" must be" (Greenfield, 2006, p. 70). In their most basic sense, 4D products are driven by functional and emotional requirements, to enhance the human experience in some way that relates to performance, safety, comfort,

Figure 2. James Novak, Dynaero 2.0 with prototype mobile application 2016, polyamide 3D printed



ergonomics etc. While ideally these will be engaging aesthetic transformations, the examples discussed here are all driven from a need to improve the functional characteristics of the object with measurable results. However, this is the starting point for the development of 4D products rather than their conclusion.

THE 4D LANDSCAPE

Products that are 4D relate to the field of responsive architecture that emerged in environmentally responsive building practices (Meagher, 2014). In Jean Nouvel's Institut du Monde Arabe, the building's facade includes hundreds of mechanical diaphragms that open and close in response to the changing climate to regulate building temperature and lighting. The Al Bahar Towers in Abu Dhabi, designed by Aedas Architects, features a similar mechanically responsive climate control façade. Designed to suit the harsh desert weather, the façade elements open and close as the sun tracks around them, shutting the building off from direct sun to keep them cool, and then opening as the sun passes to let in natural light without the heat. It is estimated that such a system could reduce solar gain by up to 50% (Cilento, 2012). Both examples use sensors and weather simulation to control the facades, operating as ubiquitous systems with no need for human control. They are also designed to improve the experience of users inside through temperature control and exposure to natural light.

The development of 4D products can also be related to the emerging field of 4D printing, a term coined by the head of Massachusetts Institute of Technology (MIT)'s Self-Assembly Lab, Skylar Tibbits. In his own words:

4D printing... entails multi-material prints with the capability to transform over time, or a customized material system that can change from one shape to another, directly off the print bed. This technique offers a streamlined path from idea to reality with performance-driven functionality built directly into the materials. The fourth dimension is described here as the transformation over time, emphasising that printed structures are no longer simply static, dead objects; rather, they are programmably active and can transform independently. (Tibbits, 2014, p. 119)

4D printing uses 3D printing technology to create structures capable of transforming shape over time under certain stimuli, including liquids or electrical current. This means the object created by the printer will not initially look like the object 15 minutes later, or a week later, or a year later. The object is "programmed" to morph into various states under specific conditions, with much in common to the bioLogic garment discussed earlier. In fact, it is possible to imagine bioLogic as a 4D print as it too uses multiple materials in order to create the opening effect of the panels. However, it currently uses screen-printing techniques to layer materials rather than a 3D printer. The development and application of 4D printing can be considered as related to the broader development of 4D products, and has potential to be a valid method of manufacturing a 4D product similar to the bioLogic garment. Tibbits acknowledges this idea, suggesting that it is the broader ideas around 4D printing that are of significance. The opportunities—and challenges—of programming materials and what this might mean for designers and consumers (Headrick, 2015, p. 8) add to the body of knowledge for the design discipline in the evolving design landscape.

Figure 3. James Novak, MyPen customized by four test subjects 2015, ABS 3D Prints

An example of a 4D printed product is the "Minimal Shoe" by Christophe Guberan and Carlo Clopath from MIT's Self-Assembly Lab. The shoe starts out as a shallow 3D print created with Fused Deposition Modeling (FDM) printed over a stretched textile. When removed from the printer, the material automatically folds itself into a three-dimensional shoe, and will further morph to suit the wearer's foot over time. This can be combined with other materials for the shoe sole for durability as a hybrid manufacturing approach, allowing for greater customization. This type of product has movements free of electronics, whereas 4D products, such as the Dynaero helmet or BMW concept cars, rely on actuators, power and programming and change the relationship between users and products. For example, although fountain pens were often valued objects, disposable pens have generally superseded these invested objects. However, if a person's relationship to the use of a pen were regarded as a system, then advances in digital technology create a different approach to design. "MyPen", published in the proceedings for the 2015 Drawing International Brisbane conference (Novak, 2015), embeds sensors in a pen that detect the user's grip and how the pen moves through space. This information can be used to 3D print a customized pen that can be embedded with sensors that monitor the evolution of a person's grip over time—short term, for different uses or from childhood to adulthood. Each evolution of the print refines the grip, responding to changes of writing style or weaknesses or strengths in the hand. Further, this system allows for change in consultation with a clinician if the user experienced difficulties, for example, following a medical incident, such as a stroke. This is arguably a form of evolutionary robotics, or alternatively part of what A. E. Eiben terms the Evolution of Things (Eiben, 2014), and figure 3 shows four different pens customized to the grip and aesthetic preference of four different test subjects in Novak's study.

Just as MyPen builds a body of knowledge on the evolving requirements of an individual, product designer Tom Dixon used digital technology to build up a body of cultural knowledge. He embedded the cultural history in a product, designed to evolve over time when he relaunched second-hand Artek stools on the market with the story of where they had previously been used contained in an RFID chip and accessed by smart phone (Loy, 2008). In *Sustainable by Design* (2006), Walker discusses building such opportunities for emotional connections between people and objects to invest objects with additional meaning to keep the product in use for longer, spreading the embodied energy invested in its manufacture. Digitally enabled 4D products designed for socio-cultural sustainability embed more than technology; they embed cultural information, such as storytelling, images, sounds and other sensory information specific to an individual or a group. This approach builds shared memory into product systems that supports the evolution of the group, and retains and enhances community. Based on this approach, conventional ideas of digital customization through 3D printing and parametric modeling have to change, with products customized through engagement, building value through use because of the embedded cultural connections. A 4D product may therefore itself change over time, or may spawn a new iteration of itself when it senses it is no longer performing optimally, or it may change as information tagged to that product or provided as data to a system is updated. This begins to describe what Bruce Sterling calls SPIMES, objects that:

...begin and end as data. They are designed on screens, fabricated by digital means, and precisely tracked through space and time throughout their earthly sojourn. SPIMES are sustainable, enhanceable, uniquely identifiable, and made of substances that can and will be folded back into the production stream of future SPIMES. (Sterling, 2005, p. 11)

With the digital revolution, and complex sustainability imperatives, including socio-cultural sustainability as well as environmental, and the aspirations for a society that responds to inclusion and diversity there is a shift towards the fourth dimension that will impact the man-made world, from the macro to the micro. This challenges what it means to be a designer and raises the question as to what degree this will affect human development in an increasingly digital age. Responsive architecture, 4D products, and 4D printing together suggest how designers are embracing new technologies with an understanding of the flux attached to rapid technological development, choosing to embed their designs with the capability to change and adapt to a changing world.

EMPOWERING PRODUCTS

It has been shown how the relationship between designers and products inherently changes as the designer's role moves from creating single products for mass production, to more of a systems approach where products change over time. The relationships between consumers and 4D products are likely to be different to those already in existence and need to be studied. This is suggested by the emotional responses noted in "The Never Hungry Caterpillar" project. At a functional level, this is an extension cable for the home designed by Matthias Laschke, Marc Hassenzahl, and Sarah Diefenbach (2011). However rather than blending into the background, this device will squirm, twist and turn as if in pain when it detects devices wasting power in standby mode, using "the metaphor of a caterpillar [to] touch upon (at least some) people's tendency to help and take care of living things" (Laschke et al., 2011). Trial users in the study could not help but unplug devices in standby mode to stop the perceived "pain" of the device. Of course "technically, the Caterpillar could just detect connected devices in stand-by and simply switch them off automatically. This would be practical, it would save energy, but it would not engage in any argument or dialogue" (Laschke et al., 2011).

This type of product is 4D in nature, having the capacity to autonomously transform in order to affect the habits of the user. What is particularly important to consider in 4D products, especially those that may be as life-like as The Never Hungry Caterpillar, is the psychological and emotional connection between users and such products, who may begin to see them as living entities to be cared for like a pet, rather than an inanimate object with little value as would be the case of a standard extension cord. This is highlighted in the work of Moyle et al. (2013) on the use of robots in the care of Alzheimer patients, where the emotional relationship between the robot and the user was explored through studies on robotic animals and toys. What happens when these "living" products stop working? Will users be more likely to try and repair these products than throw them away, much like a beloved family pet, and could this be a response to more sustainable design? With 4D products only newly emerging through research it is difficult to say, however it is conceivable based on research in robotics that this will be the likely scenario. Matthias Scheutz explores these unidirectional relationships, explaining that robots:

… affect humans in very much the same way that animals (e.g., pets) or even other people affect humans. In particular, the rule-governed mobility of social robots allows for, and ultimately prompts, humans to ascribe intentions to social robots in order to be able to make sense of their behaviors (e.g., the robot did not clean in the corner because it thought it could not get there). The claim is that the autonomy of social robots is among the critical properties that cause people to view robots differently from other artefacts such as computers or cars. (Scheutz, 2011, p. 207)

Scheutz uses numerous examples to evidence this trend, from soldiers becoming attached to robots used to detect and detonate improvised explosive devices in Iraq, to the popular robotic Roomba vacuum cleaner and the personality's people ascribe to them. As such, new scenarios and systems become important long-term considerations for 4D products, including the necessity to provide better means for product repair and maintenance, ethical regulation to prevent products influencing humans to do things inappropriate or outside their normal behavior, psychological and counseling services to help people move on after a product 'dies', control over product memory so that traits or sensitive data can be removed when a product is sold second hand. As technology moves closer to nature, these considerations will transform the relationship between consumers and products, and the industries built around them.

In responding to the ideas expressed in this chapter about human empowerment in an increasingly technological age, it might be assumed that ambient intelligence would be at odds with ideas of enhancing the human experience based on empowerment. However, this would be an oversimplification. Ubiquitous computing might be a utopian ideal, alongside modernist ideas of houses as "machines for living", but the development of ambient intelligence just needs to be developed with an underlying recognition of the importance of empowerment in the same way environments must focus on human emotion, social interaction and behavior rather than being completely machine-like. Light bulbs that wirelessly transmit their status and trigger a replacement order, as shown at the 2013 *The Future Is Here* exhibition in the London Design Museum walk a fine line between enhancing the human experience through the development of freedom from day to day minutia, and alienating people from their environment. Complete freedom from responsibility can equate to feelings of a loss of control. This is not aligned with current aspirations for society, and alternative strategies, such as delegation, should be considered in the development of the product service system.

There's a tendency in connected products and service design to assume that having machines take over human work is a good in itself….however, there are good reasons to treat automation as a choice, not a default. Instead of talking about automation, philosophers of technology often talk about 'delegation'—that is, the distribution of responsibility and effort among different kinds of humans and machines. (Rowland et al., 2015, p. 211)

However, there is an opposing argument that computing provides humans with the opportunity to extend their faculties and connection to the real world, becoming more sensitive to the nuances of their surroundings and better informed about the systems that operate within it. For example, MIT have embedded sensors into marshland (Tidmarsh, Plymouth, Massachusetts) and even their Media Lab building. This allows users to virtually explore the landscape, honing in on details such as pockets of noise, or temperature change that would otherwise be impossible for individuals to be aware of. This has the potential to create people with a very different sense of the world, in the same way that television and the Internet has changed collective understandings of the world by different populations (depending on the way it is presented). That shift in perception, triggered by an increase in information, causing a transformational change in understanding is illustrated by, for example, the reported impact of the first image of the earth taken as the Apollo rounded the moon in 1968.

Although the signs have been there with augmented reality products such as Google Glass and QR codes, Pokémon Go has heralded in a democratization of augmented reality technology that has the potential to change the human perception of the world and interactions with their environment and each other. Kuniavsky makes the comment that to have computing embedded in a forest would make no sense "…in an office it is not surprising to have wires running under the floor, but forest trees with embedded electronics seem wrong" (Kuniavsky, 2010, p. 286), yet if that technology allowed the individual to walk through the forest with the option of technologically heightened senses, they could zoom in on the movement of insects in the forest floor, hear chicks hatch high above their heads, feel the direction and strength of the wind at the top of the trees. Biohackers such as Stelarc and Neil Harbisson suggest that information sent to the brain in any form can be learned and interpreted by the brain to increase the information received through traditional senses. Augmented experience and ambient intelligence could have the potential to support the human development in a digital age if the focus is on the human experience.

Even so, the inevitability of unexpected consequences could have an equally negative impact on development. Will real life become less real? As the opportunities provided by ubiquitous computing create temptations for designers to strive for all encompassing systems, the ability to opt out at any point must be provided. The most amazing technology in the world "…will mean little if we don't, as individuals, have genuine power to evaluate its merits on our own terms, and make decisions accordingly…a paradise without choice is no paradise at all" (Greenfield, 2006, p. 247).

CONCLUSION

While there is a cautionary note in working with the power of digital technology in human-centered products, the ontogenetic adaptation capabilities of humans should allow for the evolution of the collective to rise to the opportunities—and challenges—digital technology provides. The essential criteria, though, involve designing in context, and not get swept along with what is technologically possible, but rather what responds to design theory, aspirations and values for now, for positive human development. That is, for designs to align with current thinking about sustainability, connectivity, experience-centered design, design for change, and to support inclusion and diversity.

As defined here, 4D products are about responding to the drivers behind design now, and working with time as an essential ingredient of that design approach. Going beyond the design of customizable, parametric models for individual 3D printing, and beyond the design of products embedded with sensors that send information to a management system, and going beyond augmented reality, 4D products are capable of changing over time. Ideas evolve, people's needs and desires change. Sustainability drivers support the idea of designing for that change. Digitally enabled 4D products are an emerging class of products that work towards these ideals, in sync with the natural flux of human behaviors, needs and learning.

This shift from static, resolved 3D products that make up today's retail market to 4D products is only beginning to emerge. It has the potential to encompass the next state beyond cradle to cradle, with an iterative development lifecycle, rather than a rehabilitated but still linear lifeline. The proposal is that they can work with the reality of human behaviors and interactions. The assumption will be that they require repair and are therefore designed for that inevitability, and be flexible enough to have their functionality revised and updated over time. They will be responsive, agile, and embedded with information on how to use, how to repair, and how to alter for new needs—data is their life-blood.

What does that mean for designers? What does it mean in terms of the use of technology in products? What does it mean in relation to the psychology of those products? If an essential driver for selling products is for economic growth, then there will be significant changes in how economic growth is sustained. In the past, products made for manufacturing utilized as many common components as possible, and costs of tooling constrained ideas of iterative change. Digitally enabled design has the potential to alter understandings of systems of products and production, not only for practical reasons, but also in response to the normal, human desire for change. The need now is to expand this approach to a more fluid, flexible, empowering approach. Design can become more iterative, allowing for bespoke development and evolution of products. This ability for customization in a technological era responds to the need for designers to keep referring back to the human-centered core in their design work, highlighted by Greenfield (2006, p.13): "It would be wise for us all to remember that, while our information technology may be digital in nature, the human beings interacting with it will always be infuriatingly and delightfully analogue".

The difficulty of designing in this way is that even basic designs are creating complex problems for teams across disciplines. If designers are to respond effectively, creating positive product experiences that respond to the aspirations for society at this time, they need to be basing their work on updated understandings of the human psyche and ecological interconnection as well as the technological opportunities and potential pitfalls. A new approach to the education and development of designers and teams working in this space needs to be devised, and, fundamentally, a paradigm shift in thinking and research is needed to keep pace with designing for the human experience in a digital age.

REFERENCES

Abel, B. V., Evers, L., Klaassen, R., & Troxler, P. (2011). *Open design now: Why design cannot remain exclusive*. Amsterdam, Netherlands: BIS.

Ahluwalia, P., & Miller, T. (2014). The prosumer. *Social Identities*, *20*(4-5), 259–261. doi:10.1080/13504630.2015.1004830

Alam, F., Chowdhury, H., Elmir, Z., Sayogo, A., Love, J., & Subic, A. (2010). An experimental study of thermal comfort and aerodynamic efficiency of recreational and racing bicycle helmets. *Procedia Engineering*, *2*(2), 2413–2418. doi:10.1016/j.proeng.2010.04.008

Aldersey-Williams, H. (2011). *The new tin ear: Manufacturing, materials and the rise of the user-maker*. London: RSA Design Projects.

Anderson, C. (2014). *Makers: The new industrial revolution*. New York, NY: Crown Business.

Assa Ashuach Studio. (2016). Retrieved from http://assaashuach.com/#!/portfolio/assa-studio-micro-3d-design/0

AutoDesk. (2016). *Project Shapeshifter*. Retrieved from www.shapeshifter.io

Bezirtzis, B. G., Lewis, M., & Christeson, C. (2007). Interactive evolution for industrial design. In *Proceedings of the 6th ACM SIGCHI conference on Creativity & Cognition* (pp. 183-192). New York, NY: ACM. doi:10.1145/1254960.1254986

Boyle, M. (2014, June 23). *Nestle aiming to develop a Nespresso of nutrients*. Retrieved from http://www.bloomberg.com/news/articles/2014-06-22/nestle-aiming-to-develop-a-nespresso-of-nutrients?_ga=1.134810162.210344514.1402054238

Braungart, M., & McDonough, W. (2002). *Cradle to cradle: Remaking the way we make things*. New York, NY: North Point Press.

Cilento, K. (2012, September 5). Al Bahar Towers responsive facade / Aedas. *Archdaily*. Retrieved from http://www.archdaily.com/270592/al-bahar-towers-responsive-facade-aedas

Dean, L. T. (2016). *Future factories.* Retrieved from www.futurefactories.com

Eiben, A. E. (2014). *In vivo veritas: Towards the evolution of things.* Paper presented at the 13th International Conference on Parallel Problem Solving from Nature, Ljubljana, Slovenia. doi:10.1007/978-3-319-10762-2_3

Fischer, G., & Scharff, E. (2000). Meta-design: design for designers. *Proceedings of the 3rd conference on Designing interactive systems: Processes, practices, methods, and techniques* (pp. 396-405). New York, NY: ACM.

Four-dimensional. (2010). *Oxford Dictionary of English* (3rd ed.). Oxford University Press.

Fuad-Luke, A. (2009). *Design activism: Beautiful strangeness for a sustainable world*. London: Earthscan.

Fung Kwok Pan. Fluid vase. (2010). *Design Boom Newsletter 440071*. Retrieved from http://www.designboom.com/technology/fung-kwok-pan-fluid-vase/

Gore, A. (2013). *The future*. New York, NY: Random House.

Greenfield, A. (2006). *Everyware: The dawning age of ubiquitous computing*. Berkeley, CA: New Riders.

Hawken, P., Lovins, A., & Lovins, L. H. (2000). *Natural capitalism: The next industrial revolution*. London: Earthscan.

Headrick, D. (2015). 4D printing transforms product design. *Research-Technology Management*, *58*(2), 7–8.

Hu, S. J. (2013). Evolving paradigms of manufacturing: From mass production to mass customization and personalization. *Procedia CIRP*, *7*, 3–8. doi:10.1016/j.procir.2013.05.002

Kelly, K. (2010). *What technology wants*. New York, NY: Penguin Group.

Klanten, R., Ehmann, S., & Hanschke, V. (2011). *A touch of code: Interactive installations and experiences*. Berlin, Germany: Gestalten.

Kuniavsky, M. (2010). *Smart things: Ubiquitous computing user experience design*. Burlington, MA: Morgan Haufmann.

Laschke, M., Hassenzahl, M., & Diefenbach, S. (2011). *Things with attitude: Transformational products.* Presented at the Create 11 Conference, Shoreditch House, London, UK. Retrieved from http://static1.squarespace.com/static/52722face4b02a66778dc9d0/t/53318711e4b09837d5a328f8/1395754769468/Laschke%2C+Hassenzahl%2C+Diefenbach+-+Things+with+attitude+Transformational+Products+-+2011.pdf

Loy, J. (2008). Strategies for teaching sustainable design practice with product design students. *Proceedings of E&PDE 2008, the 10th International Engineering and Product Design Education Conference* (pp. 491-496). Design Society.

Loy, J., Canning, S., & Haskell, N. (2016). 3D printing sociocultural sustainability. In S. S. Muthu & M. M. Savalani (Eds.), *Handbook of sustainability in additive manufacturing, environmental footprints and eco-design of products and processes* (pp. 145–168). New York, NY: Springer. doi:10.1007/978-981-10-0549-7_7

Loy, J., Canning, S., & Little, C. (2015, June-July). *Digital industrial design*. Paper presented at the International Design Technology Conference, DesTech2015, Geelong, Australia.

Makepeace, J. (1995). *Makepeace: Spirit of adventure in craft and design*. London: Octopus.

Massachusetts Institute of Technology. (2015). *MIT App Inventor*. Retrieved from http://appinventor.mit.edu/explore/

McEwen, A., & Cassimally, H. (2013). *Designing the Internet of Things*. Oxford, UK: John Wiley & Sons.

McLeod, S. A. (2016). *Maslow's hierarchy of needs*. Retrieved from www.simplypsychology.org/maslow.html

Meagher, M. (2014). Responsive architecture and the problem of obsolescence. *International Journal of Architectural Research*, *8*(3), 95–104.

MIT Media Lab. (2016). *Scratch*. Retrieved from https://scratch.mit.edu/

Moyle, W., Beattie, E., Jones, C., Klein, B., Cook, G., & Gray, C. (2013). Exploring the effect of companion robots on emotional expression. *Journal of Gerontological Nursing*, *39*(5), 46–53. doi:10.3928/00989134-20130313-03 PMID:23506125

Novak, J. (2015). *Drawing the pen: From physical to digital and back again.* Presented at the Drawing International Brisbane Conference, Brisbane, Australia. Retrieved from http://static1.squarespace.com/static/55779bbce4b004acf1e1479d/t/56aef970b6aa60cdf1c253d6/1454307702608/JAMES+XXXX_DRAWING+THE+PEN_DIB2015.pdf

Nowak, P. (2015). *Humans 3.0: the upgrading of the species*. London: Harper Collins.

Parametric Parts. (2016). Retrieved from http://www.parametricparts.com/

Pei, E. (2014). 4D printing: Revolution or fad? *Assembly Automation*, *34*(2), 123–127. doi:10.1108/AA-02-2014-014

Petrova, M. (2014). Educating designers from Generation Y: Challenges and alternatives. In *DS 78: Proceedings of the 16th International conference on Engineering and Product Design Education (E&PDE14), Design Education and Human Technology Relations* (pp. 524-529). New York, NY: ACM.

Philips Hue. (n.d.). Retrieved from http://www2.meethue.com/en-au/

Pokémon Go. (n.d.). Retrieved from http://www.pokemongo.com/

Powell, R. (2012). The future of human evolution. *The British Journal for the Philosophy of Science*, *63*(1), 145–175. doi:10.1093/bjps/axr027

Renishaw. (2014, February 2). *First metal 3D printed bicycle frame manufactured by Renishaw for Empire Cycles*. Retrieved from http://www.renishaw.com/en/first-metal-3d-printed-bicycle-frame-manufactured-by-renishaw-for-empire-cycles--24154

Rowland, C., Goodman, E., Charlier, M., Light, A., & Lui, A. (2015). *Designing connected products: UX for the consumer internet of things*. Sebastopol, CA: O'Reilly.

Scheutz, M. (2011). *The inherent dangers of unidirectional emotional bonds between humans and social robots. In Robot ethics: The ethical and social implications of robotics* (pp. 205–221). Cambridge, MA: The MIT Press.

Shugrina, M., Shamir, A., & Matusik, W. (2015). *Fab forms: Customizable objects for fabrication with validity and geometry caching*. Paper presented at the ACM Siggraph 2015, Los Angeles, CA. Retrieved from http://cfg.mit.edu/content/fab-forms-customizable-objects-fabrication-validity-and-geometry-caching

Sparke, P. (1987). *Design in context*. London: Quarto Books.

St Clair, A. (2016). Critical thinking, wisdom and paying homage to the human experience. *Voices, 42*(1/2), 41-43.

Sterling, B. (2005). *Shaping things*. Cambridge, MA: MIT Press.

Szondy, D. (2016, March 9). BMW looks to the future with shape-shifting. *Vision Next 100 Concept.* Retrieved from http://www.gizmag.com/bmw-group-vision--next-100-concept/42194/

Tibbits, S. (2014). 4D printing: Multi-material shape change. *Architectural Design*, *84*(1), 116–121. doi:10.1002/ad.1710

Tseng, M. M., Jiao, R. J., & Wang, C. (2010). Design for mass personalization. *CIRP Annals: Manufacturing Technology*, *59*(1), 175–178. doi:10.1016/j.cirp.2010.03.097

Walker, S. (2006). *Sustainable by design: Explorations in theory and practice*. London: Earthscan.

Weimer, M. (2002). *Learner-centered teaching: Five key changes to practice*. San Francisco, CA: Jossey Bass.

Weiser, M. (1991). The computer for the 21st century. *Scientific American*, *265*(3), 94–110. doi:10.1038/scientificamerican0991-94 PMID:1675486

Yao, L., Ou, J., Cheng, C.-Y., Steiner, H., Wang, W., Wang, G., & Ishii, H. (2015). bioLogic: Natto cells as nanoactuators for shape changing interfaces. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (pp. 1-10). New York, NY: ACM. doi:10.1145/2702123.2702611

KEY TERMS AND DEFINITIONS

Additive Manufacturing (3D Printing): A process of producing three-dimensional forms directly from 3D computer data by depositing material layer by layer. This is in contrast to subtractive manufacturing, whereby material is removed from a solid piece of material to reveal the final object.

Generation Y (Gen Y): People born between approximately 1980 and 1995.

Human-Centred Design: An approach to design where the user remains at the forefront of all design decisions, resulting in solutions that are more in tune with user needs.

Industrial Design: A profession responsible for developing the form and function of physical products, traditionally for the intention of mass production.

Internet of Things (IoT): Extends the concept of ubiquitous computing by adding the element of the Internet, allowing objects to communicate with each other or the cloud.

Ontogenetic: The entire sequence of events influencing the development of an organism.

Stasis: A state in which there is no action or progress.

Ubiquitous Computing: The concept of embedding computing capabilities into any ordinary object, in any location. May also be known as "pervasive computing".