Innovation is often perceived as an unmanageable phenomenon. Design introduces creative problem definition, such that science knowledge can lead to innovation. Simon (1968) alludes to the tension between science and its practical applications in his discussion, *The Sciences of the Artificial*. This paper explores the relationship between the two fields of science and design through C-K Theory. Four case studies are analysed through the deconstruction of a C-K map - a tool that allows a project to be described based on the way ideas and information have developed over time. The findings present three new models within the C-K theory construct; (i) the E-ladder; (ii) the K-space spiral and (iii) the double helix. Implications and future work for these three new models are explored and presented.

8 Introduction
Innovation has been defined as “the multi-stage process whereby organisations transform ideas into new/improved products, service or processes, in order to advance, compete and differentiate themselves successfully in their marketplace” (Baregheh, Rowley & Sambrook, 2009, pp. 12). The relationship between design and innovation has been explored by a variety of fields such as design (Wrigley, 2017; Verganti, 2009), business (Brown, 2008), and management (Martin, 2009). This is largely due to design being viewed as a critical strategic resource, revealed through the success of organisations such as Apple, Proctor and Gamble, and General Electric. Design, and the notion of design thinking and design innovation, is offering alternative approaches to traditional, internal improvement approaches as the key source for innovation. The value of design comes through capturing new knowledge and the designer’s ability to consistently reframe scenarios and possibilities in close creation with users. Traditionally, design has been practiced in a fairly deductive manner – working from a broad range of ideas and concepts and gradually placing constraints around those concepts through prototyping and observation. However, the Oxford Dictionary (2017)
defines the scientific method as a process of “systematic observation, measurement, and experiment, and the formulation, testing, and modification of hypotheses”. It is this process of questioning and testing that, in its rigour yet simplicity, has established both fundamental scientific laws and conceptual future technologies. Conversely, it would be myopic to assume that the scientific method is all that is needed for science to truly achieve innovation. This raises a question of metrics – how is “good” or “successful” scientific achievement measured? In traditional research contexts, it is almost exclusively the case that publications and patents designate the success of a research process. Yet a brief exploration through historical inventions reveals that this does not suffice. For example, the invention of the laser (Gould, 1959) stemmed from extensive reputable research in optical and quantum physics, yet the majority of its practical uses in electronics and spectroscopy were not established until decades later. Conversely, an invention such as Google Glass had copious investment in prototyping and user trials long before the details of its design and technology had been sufficiently defined, and the product was thus discontinued (Crothers, 2015).

From the perspective of science, the invention of the laser would be called an instant success (new knowledge and publications) and Google Glass a failure (lack of knowledge resulted in a weak product). But an intuitive conclusion would be that neither of these inventions were able to achieve innovation. There is currently a gap in understanding that the scientific method cannot close on its own, and that is in how we understand the value, and impact of research – how we create innovation. Therefore, this study aims to explore the role of design as an invaluable tool to improve both scientific process and outcome, in its ability to bring new meanings and directions to research. Through an exploratory case study approach, C-K theory (Hatchuel & Weil, 2003) was implemented as the analysis framework.

9 A brief history of design and science

Science in its most traditional forms does not generally extend beyond knowledge and into the field of design. Simon (1968) pinpoints the issue as a perceived risk of losing scientific rigour in the creation of a design artefact. However, it is in fact design, this “interface between the inner and outer environments” (Simon, 1968, p. 113), that ensures scientific knowledge can be more than just knowledge, exploring the breadth of applications while retaining depth of information. Cross, Naughton and Walker (1981, p.1) suggest that the hesitation to deviate from pure scientific method is not due to the innate value in these methods, rather the value in science as is – “rationality, neutrality, and universalism”. This opens up doors for conjecture – traditionally, science would reject speculation, while their argument is that all scientific theories in themselves rely on hypotheses of the unknown, and their ability to be falsified. The boundary between design method and scientific method is blurred, as while they are varied approaches to problem solving, both are seeking the problem to be solved.

This is also explored in Willem (1990) study Design and Science, explaining that science and design be two different pursuits of the same thing – understanding of the world. While science is deemed to be a continuous process of building knowledge, design is less concerned with production and more the application of knowledge. However, Willem (1990, p. 45) states that the two are intertwined, in that “it is only through design that science is made visible”. Here, design is seen as a “lens” into the world of science: that “science knowledge is part of the fabric with which designer’s design” (Willem, 1990, p. 44). Science is described as the foundations of design, with design the necessary intelligence that perceives and meets a need. Design introduces creative problem definition, such that science knowledge can lead to innovation.

Bonsiepe (1995) and Luo (2015) extend the discussion that there is a need for collaboration between the realms of design and science by describing the interconnected process of innovation. Science innovation is described (Bonsiepe, 1995) as being evidential and cognition-based, pursuing the goal of truth (knowledge). Design innovation involves evaluation and ideation, creating novelty in
The notions of technology and entrepreneurship sub-processes also highlight that both science and design are grounded by the “real world” and the need to “continually experiment, collect feedback, and learn through trial and error” (Luo, 2015, p.8). Both works emphasise that each process is co-dependent and the path to innovation is non-linear – all are mutually beneficial, and if any are lacking, true innovation halts.

This concept is brought to the context of a research organisation by Simpson and Powell (1999). Driven by the idea that the innovation output of a team is a direct result of its organisational structure, they describe four design archetypes for a research organisation:

- **Solitary Genius:** a traditional view of autonomous scientists pursuing knowledge for the sake of discovery, but struggling in response to rapid lateral expansion in complex technology.
- **Technology Push:** shifting focus to product and process development, with “a strong emphasis on the progressive refinement of specialist expertise” (Simpson & Powell, 1999, p. 442) – at the risk of impractical segregation into single-discipline teams.
- **Market Pull:** an antithesis to the Technology Push, relying on market driving forces to direct the flow of research, introducing non-traditional roles for those outside scientific industry – but ultimately sacrificing creativity.
- **Multiple Project:** a middle ground between the latter two archetypes, where a balance of creative invention and grounding in market reality is met – the ideal research team.

This quest for common middle ground yet again adamantly asserts the “coupling between science, technology and the marketplace” (Simpson & Powell, 1999, p. 443), this is also supported by Bonsiepe (1995) and Luo (2015). It is clear that there is a need for collaboration between design and science, or even an assertion that the two are inseparable to begin with. However, what is still to be explored in depth, is how this is achieved as an approach and process.

### 10 Exploration of C-K theory

Hatchuel and Weil (2003, p.1) introduce C-K theory, motivated by the notion that “design theory should have robust theoretical roots linked to well recognised issues in logic”. Design is portrayed as a process by which knowledge can evolve, while still achieving a goal of creativity and imagination. In essence, it establishes two spaces: K, the “knowledge space”, and C, the “concept space”, such that we “define design as the process by which a concept generates other concepts or is transformed into knowledge” (Hatchuel & Weil, 2003, p. 9). A proposition of K (essentially ‘a piece of knowledge’) is required to have some logic value – be it true/false, fuzzy logic, or another defined status.

Conversely, concepts in the set C are considered impossible to prove and hold no logic value. The power of the model lies in the interactions between the C-K spaces in terms of external (K→C, C→K) and internal (K→K, C→C) operators:

- **K→C:** this is referred to as “disjunction”, where current knowledge is reimagined into concepts and ideas, expanding the C space,
- **C→K:** this is referred to as “conjunction”, in an attempt to transform a concept into a finished product, becoming accepted knowledge,
- **K→K:** this is the trivial expansion of the K set, where available data and knowledge are added and subtracted from the process as required, and new knowledge is created from existing knowledge,
- **C→C:** this is the exploration and development of concepts mapping to new concepts.

These four operations can be visualised in the ‘design square’ (Figure 1). Each side of the square describes the process by which a C-K operator is performed. Further, a C-K map can be derived as a visualisation of the project’s design process, as seen by the generic example in Figure 2.
Hatchuel, Le Masson and Weil (2004) later express that scientific research is thus innately a ‘design issue’, since it “aims to create K-expansions, yet these expansions should be driven by some C-expansions; thus, it could help to consider research as an innovative design situation” (Hatchuel, Le Masson & Weil, 2004, p. 5). Two main approaches to the C-K mapping process are further outlined, depending on if the research is part of a science-based project (SBP) or creativity-based project (CBP). SBPs generally exist within a specialised but narrow K set (Large, 2017), and are searching for outside-the-box applications of niche knowledge. Hatchuel, Le Masson and Weil (2006) describe this to be a breadth-first approach, where despite limited knowledge, we expand on a variety of C sets and apply narrow K in non-classical scenarios by expansive partitions. Alternatively, CBPs are often expansions of a very general or common knowledge base, and run the risk of being overwhelmed by an unlimited C set. More suitably, a depth-first approach refines the conceptual process to avoid growing overwhelmed by attractive but potentially unviable choices. This is where the visualisation of a C-K map becomes integral – its depth and/or breadth can be used to estimate the success or failure of a project (Hatchuel, Le Masson & Weil, 2006). Here we are presented with a rigorous design paradigm that not only formalises the research process, but assists in the assessment of a successful research project by alluding to an ideal C-K map layout. Perhaps a C-K map of the aforementioned laser would reveal too narrow thinking, or Google Glass an uncontrolled or shallow ideation process.

Despite this clear need and ability of C-K theory to promote innovation, there is a gap in the literature in terms of a model or framework for the application of C-K theory to scientific research. The proposal to use C-K theory to establish common ground (Chen et al., 2017) is a critical one – for collaboration to occur, parties must first speak the same language. The success of this
expansive design dialogue in the business field, combined with the known value of using C-K theory in collaborative contexts, allows us to consolidate the previous gaps in knowledge, and raise a new research question: How can C-K theory be used to initiate, direct, and realise innovative scientific research?

11 Case Study Analysis
A series of innovative case studies were explored in terms of their research and design process. Three separate modes of data were collected from secondary sources. Multiple data sources were sourced to gain the broadest possible range of information from a variety of perspectives to ensure coverage, range and triangulation. All data came from publicly available third-party digital resources such as websites, social media pages, online trade publications and annual company reports. The data collection for each case study began with a search of the company’s website; annual reports and other publically available information were analysed to gain an overview for each one. Following this, web searches were conducted as a precaution to discover any information not present on the other data sources. This information was mapped onto a predesigned data sheet developed by the research team. Having captured data across a diverse set of sources, the authors were able to increase the reliability and validity of the analysis by means of data triangulation (Thurmond, 2001).

11.1 Analysis Framework
The research followed a deductive structured qualitative content analysis approach (Elo & Kyngäs 2008; Nusem, Wrigley & Matthews, 2017; Straker, Wrigley & Rosemann, 2016) utilising a predetermined categorization matrix (Mayring, 2004). Having selected a categorization matrix, data were able to be coded in accordance to the predetermined categories featured in the matrix, and aspects of data which did not fall into the predetermined categories were able to be filtered out (Elo & Kyngäs, 2008). The C-K mapping process first involved an overarching description of the scope of the project. The starting point was defined as either a Concept or piece of Knowledge – questioning if the project was motivated by a need or idea (Concept) or by a gap in knowledge that needed to be filled (Knowledge). Each stage of development, as publicly reported by the research teams, was then described through C-K operators, until the final design (in this case, products) was reached in the K space. Through this attempt to infer a possible C-K process implemented by the scientists and designers involved, visualisations of innovative research were made.

11.2 Case 1: DuoSkin
The first case study is of a recent innovation in the MIT Media Lab, where there has been developed wearable technology in the form of gold leaf “tattoos” known as DuoSkin (Kao et al., 2016). The research team was inspired by the recent applications of on-skin devices in medical purposes (such as drug delivery or monitoring), and sought to bring this technology into the everyday world. Further, they worked within known outcomes in body-compatible interfaces by “repurposing accessible materials (e.g. gold leaf, thin tattoo paper) and tools (craft electronic cutter)” (Kao et al., 2016, p. 2). In C-K terminology, the MIT Media Lab performed a K→C disjunction of the known scientific and technological space in order to appropriate knowledge into new concept spaces. A process of technical evaluation in terms of user experience and product durability was implemented (driving C→C expansions). Ultimately, with the invention of a successful product, C→K conjunction was achieved (Figure 3).
11.3 Case 2: Algae Printing

Marin Sawa is a researcher at the interface of design and biology, seeking to bring real world meanings to scientific innovations. Algae Printing, a novel technology that involves developing bacterial cultures on surfaces, was in fact birthed within a biotechnology research laboratory in the Imperial College of London. Sawa (2016) proposes an intensive collaboration technique wherein designers are invited within the research laboratory through an ‘observation day’. Her hypothesis was that by harnessing the collaborative physical and social space of a research laboratory, combined with the rigour of the scientific method executed through a designer’s perspective, new innovations could be brought about. It was found that the presence of a designer disrupted systematic routine and sparked ‘non-standard scientific questions’ (Sawa, 2016, p. 68). These led to new conceptual directions, and her early innovation of using inkjet printers to print algal cells. In contrast to DuoSkin, here lies a project starting in the C space – Sawa’s hypothesis on the nature of scientist-designer collaboration was conceptual at first, then rooted in knowledge upon establishing herself within the Imperial College Photosynthesis Lab. New knowledge from the unfamiliar K space continually and broadly feeds into the C→C expansion, leading to unexpected concepts, and a final C→K conjunction that establishes new knowledge potential (Figure 4).
11.4 Case 3: Organs-on-chips
Research at the Harvard Wyss Institute was driven by a glaring need in the medical industry for reliable and fast means to develop and test chemical therapies (Henry et al., 2017). The problem space they defined was that drug development is a lengthy and costly process that, being heavily reliant on animal testing, has great implications in accuracy and ethics. Hence the development of organs-on-chips, a microtechnology wherein human organs and biological functions are replicated in a clear polymer chip, allowing medical researchers to effectively test and visualise the behaviour of new compounds. The technology has now been commercialised; Donald Ingber of the Wyss Institute outlines how they “took a game-changing advance in microengineering made in our academic lab, and in just a handful of years, turned it into a technology that is now poised to have a major impact on society” (Wyss Institute, 2017). This is a textbook example of an in-depth K space (knowledge of current medical research and microtechnology) undergoing a K→C disjunction that allows researchers to extend their work beyond what is conventional or ‘known’ into a conceptual sphere. The K space is expanding with scientific research, but having a well-defined problem space ensures that disjunctions direct the K→K expansion towards a clear goal and final C→K conjunction (Figure 5).

11.5 Case 4: Liquidity Naked Filter
The Naked Filter is a nano-engineered water purification device, compartmentalised into a water bottle. Liquidity, the start-up behind Naked Filter, is unique in its establishment – aside from the commercialisation team, there exist dozens of academics and students at Stony Brook University continually developing the nanofiber technology. The founders commenced their research based on a proposition that electro-spinning can be used to create a filtration membrane (Lee et al., 2017). This hypothesis drove years of research efforts, fuelled by industrial funding, before a final patent. The next stage was forming the Liquidity ‘Dream Team’ and commercialising the product. Research is currently continuing in terms of increasing the scale, applications, and efficacy of the filtration system (Naked Filter, 2017). This cyclical process of questioning, researching and applying has led to the company’s success and can be visualised through C-K theory. There is simultaneous iteration in the C and K spaces, with K→C disjunctions leading to innovative new concepts backed by in-depth research knowledge, and C→K conjunctions leading to prototypes and product development (Figure 6).
12 Discussion: Three New Models

The authors propose three new models from which can be derived from C-K mapping; (i) the E-ladder; (ii) the K-space spiral and (iii) the double helix. Each are detailed below with respect to the case studies in which they were identified.

Mapping the design process in C-K theory for each of these case studies yields quite distinct paths – and this is expected, as research projects are seldom identical and will of course follow different courses. However, in terms of overall driving forces and design processes involved, some interesting inferences can be made. Comparing the cases of DuoSkin and Sawa’s Algae Printing, these are both examples of Hatchuel, Le Masson and Weil’s (2004) creativity-based projects (CBPs). These projects are sparked within a conceptual space of excitement, inspired by the potential for science (traditionally, K propositions) to direct innovation. Both are successful because they further follow Hatchuel, Le Masson and Weil’s (2004) recommended depth-first approach, where instead of allowing overwhelming ideas dominate, concepts are continually grounded in an expanding research space. The hypothesised C-K maps visually reveal this, where specific technologies (in the case of DuoSkin) or general scientific input (in the case of Algae Printing) direct C→C expansion. This is not simply a depth-first process, rather outward branching into research (the K space) becomes a very significant contributor that ensures the C-space remains relevant and has substance from which to develop.

The C-K map model called the ‘E-ladder’ is where the backbone of the ‘E’ maps the C→C depth, and the ‘arms’ of the ‘E’ create roots in the K-space (note that the three arms of the ‘E’ are arbitrary, and a process may have more/less as needed) (Figure 7).
The ‘K-space spiral’, seen in the Organs-on-chips case study and is an example of a science-based project (SBP) emerging from a narrow and refined knowledge space. However, on creating a C-K map, we do not see (from the information available) an attempt to perform breadth-first concept expansion to find new applications for this niche knowledge (Figure 8). So, what makes this still a successful innovation? It is most likely due to the constant recurrence of a well-defined problem space. This ensured that research efforts were driven by a known need, such that the K→C disjunctions lead to concepts that were already solving a problem. This equipped the consequent C→K conjunction, and thus Organs-on-chips were invented. This process could potentially be named the ‘K-space spiral’, since all propositions in K return to a common problem before iterating through the evolving concept.
The Naked Filter shown through the ‘double helix’ is another SBP with a similarly iterative design process, except the focus is shifted from a problem definition to a scientific opportunity. By promoting expansion in both C and K, Liquidity was able to find creative concepts while widening the initially narrow knowledge space. The proposed model for this type of SBP is the ‘double helix’, with two ‘strands’ of concept and knowledge (Figure 9). Innovation occurs at the intersection of these two expansions, through questioning and researching.

![Figure 9 “Double helix” superimposed on the C-K map for Naked Filter, highlighting the simultaneous C and K expansions, and C→K and K→C connections.](image)

The suitability of design as an approach for the translation of scientific knowledge into application, is due to its position as a future oriented activity. The designer is situated between the world as it is, and the space that it could be (Margolin, 2007; Krippendorff, 2006; Seymour, 2008). The notion of concepts and knowledge as formal artefacts has been explored in design literature. It is widely recognised that a design outcome is not necessarily a physical object or product, rather any contribution to or expansion of knowledge (Zimmerman, Forlizzi & Evenson, 2007). Conversely, a concept is an abstract notion that results from iterative ideation – an idea to be continually refined (Zimmerman, Forlizzi & Evenson, 2007). In light of these models, the knowledge space (K) contains more than just facts and products, as it opens up the research process to any contributions to design theory and advancement of knowledge. These models provide both retrospective and proactive frameworks for science innovation through design. Possible applications could include:

- Mapping the research decisions made by a scientific research group at a university to not only visualise their path so far, but also identify potential pain points where perhaps there was not enough exploratory research (C-expansion), or insufficient questioning followed by grounding in research (as is shown to be necessary in the Double Helix model).
- Alternatively, a proactive approach could see, for example, a technology start-up on the journey of commercialisation referring to these C-K models as a guideline to promote scientific innovation. This could involve making conscious business or design choices to continually ground their concepts in the evolving research space (as seen in the E-ladder model).

The application of these models is in taking well-defined notions of logic, and applying them to expansive problem solving situations to cultivate innovative research.
13 Summary and future work
The analysed case studies confirm the assertions from literature over the past fifty years – that science and design are two paths to the same goal. However, this study has demonstrated that the shape of this path is critical in whether or not the right goal is achieved. Design, in the form of C-K theory, has been the interface between the scientific process of invention and its realisation in society, as predicted by Simon (1968). In the literal sense of a visualisation, but also in its exposure of a detailed research process, C-K theory has made the science process visible by design (Willem, 1990). C-K theory is also shown to be an effective tool for analysing research projects after their completion, by mapping out the entire design process in a highly visual technique.

The study also reveals several areas of future research, in terms of how a research collaboration could practically establish a common ground to co-generate:

- What does a successful collaboration look like, and what makes it successful?
- How can C-K theory or mapping be employed by a research organisation to prevent implausible or ineffective research outcomes?
- What new directions are possible for research organisations that employ C-K theory?

This exploratory study examined the tension between science and design in literature, and how design can fill the gap that takes scientific research from pure knowledge to innovation. There is an opportunity for the design model of C-K theory, in harnessing the collaborative nature of both science and design, to provide a framework for this innovative research.

14 References


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